ECONOMIC GEOLOGY

VOL. XXIX JANUARY–FEBRUARY, 1934 No. 1

THE EVOLUTION OF THE MINERAL COALS.

PART I.

J. VOLNEY LEWIS.

CONTENTS.

Introduction 1
Composition of the coal series 3
Swamp forest debris 3
The humic complex 6
The essential elements 7
Atomic ratios 11
Gravimetric and atomic diagrams 12
Transformation 16
The wasting processes 16
The volatile products 17
Stages of decay 20
Rotting in the air 21
Decay under water 23
Subterranean changes 25
Graphic examination of chemical changes 30
Calculation of losses 37

(*Concluded in next number.*)

INTRODUCTION.

THE swamp jungle is the ancestor of the coals. From the forest debris a progressive transformation evolves peat, lignite, the mineral coals, the high-carbon residues, and graphite. Minute intergradations link these varied materials into a unified, interlocking whole, which may be called the coal series. The transi-

tions are unidirectional and follow definite "lines of flow." Thus, the divers coals are modified forest products; but they have suffered immense losses, and the residues have been blackened, condensed, solidified, and otherwise changed so profoundly that only the microscope reveals their intimate relationship to growing plants.

From the chemical point of view these changes are retrogressive. Paradoxically, the advance in rank and fuel value is a direct result of degenerative processes. The unstable substances are broken down through a series of vast complexity to the simplest final products. While the accumulating debris is exposed to the air, drastic dissolution takes place, but the plant products differ widely in their susceptibility to decay. Hence the more resistant and most resistant materials become concentrated. In peat the undecomposed resins and waxy substances and fragments of partially decayed wood mingle in various proportions with the pasty mass of macerated tissues. These products of selective decay—relics from the ravages of the weather and the attacks of microörganisms—have entered upon the first stage of an age-long evolution.

Of all the natural raw materials, the chemistry of the coals is perhaps the least understood. The constitution of the plant substances is known in part; that of the coals, their direct descendants, is largely unknown. The problem bristles with formidable difficulties. Roughly, the rise in rank is characterized by the progressive elimination of water, the discharge of methane and volatile oxides, and a corresponding steady enrichment in carbon. In the higher bituminous and anthracite ranges, hydrogen vanishes rapidly and fuel values decline. The extreme anthracites reabsorb moisture and decline still further. Finally the subgraphites, the last of the recognizable coals, approach pure carbon in composition. In the schists the carbons of various origin have been crystallized into graphite. In these transformations the essential changes in bulk composition are all subtractive. The continuous evolution of volatile products results in heavy losses of material; hence anthragenesis, or the formation of coal, is a process of

"devolatilization." Similarly the term "carbonization" refers to the progressive enrichment of the successive residues in carbon. The process is sometimes designated by the mongrel term "coalification."

The problems of the formation and transformation of coal have called forth numerous attempts to represent the changes by means of graphs and chemical equations. Generally little more than suggestive value has been claimed for these speculations. In this category are the conjectures of Liebig, Bischof, Renault, Le Conte, and Parr. The notable progress of recent years toward the understanding of the coals may serve as the excuse for a reconsideration of certain phases of this topic. Also the point of view in this paper is somewhat different. The emphasis is placed rather upon the effort to establish approximate limits within which the mutations apparently occur, under the varied conditions in nature. Certain external processes also call for comment, as do the related phenomena of accumulation and condensation.

COMPOSITION OF THE COAL SERIES.

Swamp Forest Debris.—The origin of coal is a controversial topic of long standing. Happily intensive research has gone far toward bringing about a convergence of opinion among geologists who have delved in this field. The common coals are now widely recognized as products of the forests of fresh-water swamps. Such were the gathering grounds of the Carboniferous coals, with warm climate and copious rainfall well distributed. The coal swamps of the Mesozoic and Tertiary also record ample rainfall and mild climate, even in the polar regions.[1] Nevertheless, the common laminated structure of the coals points to seasonal changes, which doubtless involved temperature and rainfall, fluctuations of water level, and corresponding variations in the depth and concentration of the toxic solutions. With changing conditions the rate of forest growth and decay of the debris necessarily varied, as did also the resultant proportions of unde-

[1] David White, Trans. Amer. Inst. Min. Eng., vol. 71, p. 3, 1925.

composed wood and the resistant waxes and resins in the accumulating peat. The thin banding in coal is the reduced and compressed form of a coarser bedding, like that observed in the peat swamps and bogs of today.

The larger inland swamps of the East Indies and of the Atlantic Coastal Plain in the United States approximate in a small way the ancient coal-forming conditions. The warm moist climate promotes rapid growth; portions of the falling leaves, branches, and trunks of trees escape decay in the protection of the toxic waters and thus contribute to the growing deposits of peat. In the course of sedimentation some of these residues are further protected by deep burial, and eventually these become transformed into coal. Hence the vegetal debris and the peat represent the early stages of the coal-forming substances, and they must be included in any view of the sequence as a whole.

The green plants build into their solid parts intricate combinations of atmospheric carbon with the elements of water, a little nitrogen and sulphur, and small amounts of mineral matter. Thus they store up a minute fraction of the energy that comes to the surface of the earth from the sun. Chemically, these plant substances are chiefly carbohydrates of the cellulose group, including the less resistant hemicelluloses. Normal cellulose constitutes more than one half of the solid parts. It is a glucose anhydride, an isomer of starch, and it contains 44.4% of carbon, 6.2% of hydrogen, and 49.4% of oxygen; its composition may be represented by the empirical formula, $(C_6H_{10}O_5)n$. Cotton fiber, the typical example, is almost pure cellulose. Lignin, the chief non-carbohydrate, which occurs in intimate chemical or physical combination with cellulose, is also an abundant constituent of the woody plants. It appears to be a variable colloidal mixture containing about 64% of carbon, 5.5% of hydrogen, and 30.5% of oxygen; and its average composition is approximately $C_{30}H_{40}O_{14}$. Lignin is much more resistant than cellulose to fungal and bacterial decay.

Present in small variable amounts in different species of plants are numerous cell products, including starch, proteins, gums,

resins, waxes, oils, fats, pigments, and tannins. Many of these substances are richer in carbon and hydrogen than the other constituents of the plants. The fats and oils contain 74 to 78% of carbon and 10 to 13% of hydrogen; the resins 77 to 84% of carbon and 9 to 13% of hydrogen; and the waxes 80 to 82% of carbon and 14% of hydrogen. The volatile oils in woods are toxic to the destructive microörganisms; the waxes enter into cuticles and various resistant membranes; the resins afford physical protection.

The average composition of modern coniferous woods is approximately 30% lignin, 53% cellulose, 15% hemicelluloses, and 2% of waxes, oils, and resins. The hardwoods (angiosperms) in general contain somewhat less lignin and more of the hemicelluloses. In bulk composition the woody plants of every kind and from every country and climate are much alike. Hence, only slight differences in the composition of the coals can be attributed to the original plant debris. The selective decay of these substances leads to the rapid destruction of the hemicelluloses and most of the normal cellulose. On the other hand, the greater part of the lignin degenerates into the humic complex, and the resistant waxes and resins, remaining unaltered, become more and more concentrated in the residue, the greater the destruction of the other constituents.

Under certain conditions the process of accumulation also is selective, as illustrated by the segregation of the high-hydrogen cannel materials in the swamp lakes and ponds. However, the cannels, together with the splint coals and bogheads, are rare special types, in comparison with the common humus coals. Original differences, therefore, are inherited from (1) the somewhat varied nature of the original vegetal debris, (2) selective modes of accumulation, and (3) the degree of decay. On the other hand, the differences due to rank, or relative advancement in the coal series, as lignite (browncoal), bituminous coal, anthracite, depend on the degree of modification which the original material has suffered in its subsequent history. Beyond the bituminous coals the inherited, or type, differences are obliterated.

The Humic Complex.—The essential constituent of peat is a pasty black humus.[2] With it are mingled in all proportions fragments of wood and vegetable fiber in various stages of decay. In its natural state in the swamp or bog, peat is saturated with water, which may constitute as much as 90 or even 95% of its weight. Most of this water is held tenaciously in the humus, which appears to be a complex mixture of colloids. With the gradual elimination of water these substances solidify like hard rubber, and the degree of hardness and toughness in coals seems to depend primarily on this process. These properties are further enhanced by the progressive extraction of oxygen from the humic materials, thus rendering them still harder and also more resistant to heat, solvents, and chemical reagents.

Concerning the constitution of the humins little is known. Various fractions, with increasing carbon content from 46 to 64%, are soluble, respectively, in cold water, hot water, and alkaline solutions. One half of the humus remains as a peat-like insoluble residue containing 60% of carbon. Even these separate fractions are complex mixtures. Thus, in the humins, the coal series begins with an array of chemical problems of tremendous difficulty.

As noted, the common coal complex, or "conglomerate," being a modified peat, contains in varied proportions these humic derivatives and remnants of undecomposed wood, besides the highly resistant waxes, cuticles, and the coats of spore and pollen grains. Generally the humic substances constitute more than three-fourths of the mass. Of all the coal constituents these appear to be most subject to the progressive alteration that determines the rank, or state of advancement in the coal series. This alteration, in turn, gradually increases the hardness and the resistance of these substances. Thus, in peat and lignite soluble humus is abundant; in the older browncoals, however, it is soluble only in boiling alkaline solutions; in the bituminous coals, which are still further deoxidized, it is necessary to "regenerate" the humus by means of

[2] The humic complex is variously known as humus, humins, or humic acids, or as ulmins and ulmic acids. The latter terms are commonly used in British literature, the former are generally preferred in Germany and the United States.

chemical oxidizing agents, or by oxidation in the air, in order to restore their solubility in the alkalies. Such changing compounds exist in all ranks and varieties of coal, as evidenced by the continuous evolution of carbon dioxide, water, methane, and small amounts of other volatile products.

The sensitive humic substances are probably responsible for the avidity of the coals for oxygen.[3] The rapid and long-continued absorption of oxygen by all ranks and types of coal, upon exposure to the air, is accompanied by the generation of heat, but with little or no evolution of carbon dioxide or other oxides. The oxygen combines with the unsaturated humins and thus restores the soluble humic acids. This absorption accounts for the general deficiency of oxygen in the air of coal mines.

The Essential Elements.—The dominant elements of the plant substances and the coals are carbon, hydrogen, and oxygen. Nitrogen and sulphur also are essential constituents, but they are present in small quantities and do not vary according to any known law. In wood the nitrogen content is generally less than 0.5% and in coals less than 2.0%. Part of it doubtless comes from animal matter and some, perhaps, from air imprisoned in the original wood.[4] Sulphur in the coals is largely a later accession, the "organic," or constitutional sulphur from the original vegetation falling generally below 1.0%. Likewise, the greater part of the ash is attributable to the fortuitous admixture of earthy sediments in the peat-swamp stage. The essential part of the mineral matter in coals, as in most plants, is less than 1.0%. It is composed chiefly of carbonates, phosphates, and silicates of calcium, potassium, and magnesium, with smaller

[3] Francis, W., and Wheeler, R. V.: Trans. Amer. Inst. Min. Eng., vol. 71, pp. 165–174, 1925; *Ibid.*, vol. 88, pp. 438–456, 1930; Blum, I.: Bull. soc. romane chim., tome 32, pp. 45–49, 1929.

[4] Fossil plants contain little nitrogen. Ad. Carnot (Comptes rendus, vol. 99, p. 253) analyzed six specimens of acrogens from the coal beds of Commentry, France. They were perfectly preserved but were converted entirely into coal. The average nitrogen content of the six, which varied but little, was 0.43 per cent. Citing these results, F. W. Clarke (U. S. Geol. Surv. Bull. 770, pp. 769, 770, 1924) suggests that most of the nitrogen in coal may come from animal matter. (Clarke erroneously attributes the analyses to Meunier, by whom they are quoted.)

TABLE I.

COMPOSITION OF THE COAL SERIES.*

	(1) Chart Symbols.	(2) Weight Per Cent.	(3) Atomic Ratios.	(4) Atomic Per Cent.	(5) Empirical Formulas. Carbon 100.	Average Residues.	
Vegetal debris....	*V*	C 50.5	4.21	32.1			
		H 6.2	6.20	47.3	$C_{100}H_{147}O_{64}$	$C_{100}H_{147}O_{64}$	(100)
		O 43.3	2.71	20.6			
Peat.....	*P*	C 60.5	5.04	38.4			
		H 6.0	6.00	45.7	$C_{100}H_{119}O_{41}$	$C_{84}H_{100}O_{35}$	(70)
		O 33.5	2.09	15.9			
Lignite.....	*L*	C 72.0	6.00	47.1			
		H 5.3	5.30	41.7	$C_{100}H_{88}O_{24}$	$C_{71}H_{63}O_{17}$	(50)
		O 22.7	1.42	11.2			
Subbituminous....	*SB*	C 79.0	6.58	50.8			
		H 5.4	5.40	41.6	$C_{100}H_{82}O_{15}$	$C_{66}H_{54}O_{9.7}$	(42)
		O 15.6	0.98	7.6			
Bituminous.....	*B*	C 85.5	7.13	54.0			
		H 5.5	5.50	41.8	$C_{100}H_{77}O_{7.8}$	$C_{63}H_{48}O_{4.8}$	(37)
		O 9.0	0.56	4.2			
Superbituminous..	*SP*	C 92.0	7.67	59.6			
		H 5.0	5.00	38.9	$C_{100}H_{65}O_{2.5}$	$C_{62}H_{40}O_{1.5}$	(34)
		O 3.0	0.19	1.5			
Subanthracite....	*SA*	C 93.8	7.82	66.0			
		H 3.9	3.90	32.8	$C_{100}H_{50}O_{1.8}$	$C_{59}H_{30}O_{1.1}$	(32)
		O 2.3	0.14	1.2			
Anthracite.....	*A*	C 95.5	7.96	73.2			
		H 2.8	2.80	25.8	$C_{100}H_{35}O_{1.4}$	$C_{57}H_{20}O_{0.8}$	(30)
		O 1.7	0.11	1.0			
Metanthracite....	*M*	C 96.0	8.00	81.3			
		H 1.7	1.70	17.3	$C_{100}H_{21}O_{1.7}$	$C_{53}H_{11}O_{0.9}$	(28)
		O 2.3	0.14	1.4			
Subgraphite.....	*SG*	C 96.2	8.02	89.0			
		H 0.8	0.80	8.9	$C_{100}H_{10}O_{2.4}$	$C_{51}H_{5.2}O_{1.2}$	(27)
		O 3.0	0.19	2.1			
Graphite.....	*G*	C 100.0	8.33	100.0			
		H 0.0	0.00	0.0	$C_{100}H_0O_0$	$C_{51}H_0O_0$	(26)
		O 0.0	0.00	0.0			

* Median members of each recognized rank, selected from Ralston's chart of ultimate analyses (U. S. Bur. Mines, Tech. Paper 93, Pl. I, 1915). See Fig. 3.

Note: (1) that chemical analyses, column (2), are gravimetric; hence they represent relative weights of the elements, not abundance or scarcity of their atoms; (2) that, although each analysis is expressed as 100%, they represent, after the first, a series of diminishing residues; (3) losses of constituents affect the composition of the residues only to such extent as these losses vary from the relative proportions in which the elements were present originally in the wasting substance.

proportions of sulphates and chlorides and the additional metals, sodium, manganese, aluminum, and iron. These substances are taken up selectively from the soil solution, but the rôle they play in the plants is unknown. A little of this mineral matter is soluble in water, but most of it is held tenaciously in some sort of insoluble combination with the organic materials. Five to six per cent. of the potassium and calcium remains in the wood or

TABLE II.

PROXIMATE COMPOSITION AND PHYSICAL PROPERTIES OF THE COAL SERIES.
(Most common values.)

	Moisture (%).	Fixed Carbon (%).	Vol. Matter (%).	F.C./V.M. (Fuel R).	Specif. Gravity (Aver.).	Weight cu. ft. (lbs.).	Thickness (ft.).	Residue Vegetal Debris.
Vegetal debris (*V*).....	(Dry)	20–30	65–75	0.35	0.24	15	15	100
Peat (*P*).....	80–90	4–10	10–20	0.46	0.72	45	3	70
		20–30*	50–75*	0.40*				
Lignite (*L*).....	30–55	15–35	20–35	0.91	1.20	75	1.5	50
		45–55*	35–50*	1.18*				
Subbituminous (*SB*).....	12–30	35–45	25–40	1.23	1.25	78	1.2	42
		50–60*	30–45*	1.47*				
Bituminous (*B*)..	3–12	45–65	25–45	1.57	1.30	81	1.0	37
Superbituminous (*SP*)....	2–8	70–85	10–25	4.43	1.35	84	0.9	34
Subanthracite (*SA*).....	2–5	75–90	10–20	5.50	1.40	87.5	0.8	32
Anthracite (*A*)..	2–5	80–95	2–10	14.60	1.50	93.5	0.7	30
Metanthracite (*M*).....	12–24	93–98†	2–7	21.00	1.75	109	0.6	28
Subgraphite (*SG*).....	4–10	94–98†	3–6	21.30	2.00	125	0.5	27
Graphite (*G*)....	0	100	0	—	2.20	137	0.4	26

* Moisture free. † Ash and moisture free.

charcoal even after boiling in acids.[5] Water also must be regarded as an essential constituent of the coals, since the greater part of it is held as a component of the humic colloids, particularly in peat, lignite, and the low-rank bituminous coals. Free carbon is supposed generally to exist in the higher coals and to be abundant in the extreme anthracites, but no method has yet

[5] H. G. Turner (Trans. Amer. Inst. Min. Eng., vol. 88, p. 641, 1930) estimates the "fixed" or "organic" ash in the anthracites and bituminous coals of Pennsylvania as approximately 0.5%.

been devised for determining its quantity nor even for demonstrating its presence.

For present purposes it is convenient to regard the members of the coal series as essentially mixtures of organic compounds of the three dominant elements, carbon, hydrogen, and oxygen. The ash constituents, sulphur, and nitrogen, having no bearing on either the rank or the type of the coal, may be disregarded. On this basis Table I shows approximately the average composition of wood, as representative of the forest debris, and of peat and typical members of the coal series. It is based on median values selected from Ralston's chart of ultimate analyses[6] (Fig. 3). Graphite has been added as the ultimate end product. For convenience in comparison the bulk composition of these intricate mixtures is represented by simple empirical formulas. Two sets of these are included in Table I, column (5). In the first, the carbon is represented in every rank as 100, in order to show the relative decline of hydrogen and oxygen. The second shows the average residues after losses of all elements, from rank to rank, as estimated for the average transformation and represented in Graph *A*, Fig. 14. Table II shows median proximate composition and physical properties.

In marked contrast with the uniformity of the woody plants in ultimate bulk composition, peat and the different ranks and types of coal are widely variant and overlapping in all of their characters. Not only does the composition vary with different regions and different beds, but also in the products of different mines that draw upon the same bed. Marked differences are found between even the upper, middle, and lower portions of a coal seam at a single locality. In the common laminated coals the hydrogen content of the bright layers generally averages 0.4 to 0.6% higher than that of the intervening dull layers. This represents an increase of 1.7 to 2.6% on the atomic basis. The dull layers are higher in carbon. Comparable differences are found in modern peat.

[6] Ralston, Oliver C.: Graphic Studies of Ultimate Analyses of Coal. U. S. Bur. Mines, Tech. Paper 93, Plate I, 1915.

For present purposes the median values, as given in Table I, may be regarded as typical, each in its own rank.[7] They represent convenient stages in the continuous progression from jungle debris, through the common coals, to anthracite. The rarer and more specialized types, such as splint coals, cannels, and bogheads, are omitted from present consideration. Nevertheless, it is to be noted that both chemically and physically, including the minute microscopic characters, complete intergradation is found among the coals of every rank and type.

Atomic Ratios.—For purposes of interpretation and the study of transformations from stage to stage, the atomic ratios (Table I, column 3) are most convenient. These numbers are the ratios of gravimetric percentages to atomic weights; hence they are proportional to the numbers of atoms, or chemical units, present. Recalculated to the basis of 100, they are repeated in column 4 as atomic percentages. Chemically the atomic proportion of an element, rather than its weight, is the important fact.

It will be observed that hydrogen, the lightest element, shows greatly increased values on the atomic basis, as compared with the percentages by weight, as given in column 1. On the other hand, the heavier elements, carbon and oxygen, have been relatively diminished. Thus, in terms of chemical units, hydrogen (not carbon) constitutes nearly one-half of wood and peat, more than 40% of lignite and bituminous coal, and even average anthracite contains 26% of this element. Oxygen, the heaviest of the three, has dropped to approximately one-half its gravimetric values.

The elemental composition of the successive members of the coal series may be compared conveniently from the basic data given in Table I and their graphic representation in Fig. 1, A and B. The most striking feature is the continuous enrichment

[7] The nomenclature suggested by David White (Trans. Amer. Inst. Min. Eng., vol. 88, 1930, p. 489) has been followed, with the insertion of "metanthracite" for the fuel coals of Rhode Island and prefixing vegetal debris at the head of the list. "Semibituminous," "semianthracite," and "superanthracite" are avoided as confusing and misleading terms. "Bituminous" is a misnomer for the humic coals, but its universal use and the familiar common coals make its connotation clear. Metanthracite and subgraphite are only tentatively placed among a few scattered analyses.

in carbon with advancing rank. Almost equally striking is the rapid drop in oxygen through the first half of the series—from vegetal debris to bituminous coal. Throughout this range, hydrogen remains nearly constant at its maximum. In the later stages the outstanding feature is the swift decline of hydrogen, whereas oxygen is nearly constant, but at values very close to its minimum. For comparison the proximate analyses of a typical series are shown in Fig. 2.

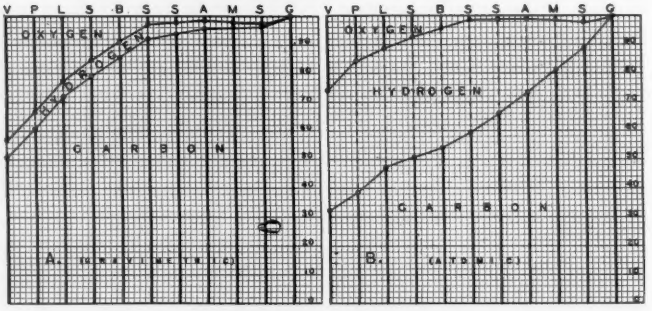

FIG. 1. Diagram showing the average elemental composition of the coal series as calculated to the "pure coal" basis of carbon, hydrogen, and oxygen; (*A*) Gravimetric basis; (*B*) Atomic basis. Initials at top indicate: Vegetal debris, peat, lignite, subbituminous coal, bituminous, superbituminous, subanthracite, anthracite, metanthracite, subgraphite, graphite.

Gravimetric and Atomic Diagrams.—When ultimate analyses are plotted as points on a system of trilinear coördinates, representing carbon, hydrogen, and oxygen, the coal series occupies the belt-like area shown in Fig. 3. Graph *A* (after Ralston), is based on the weight percentages of the elements (as in Table I, Col. 2). A fault of this chart is the over-emphasis of oxygen, which ordinarily is not determined in fuel analysis. Lacking an accurate method, the oxygen content is merely estimated by difference; hence, besides oxygen, it contains the errors from the determination of all other constituents, except to such extent as

these may happen to compensate. In a measure, carbon also is overstressed in the gravimetric percentages, since this element can not be determined with accuracy. But, gravest error of all,

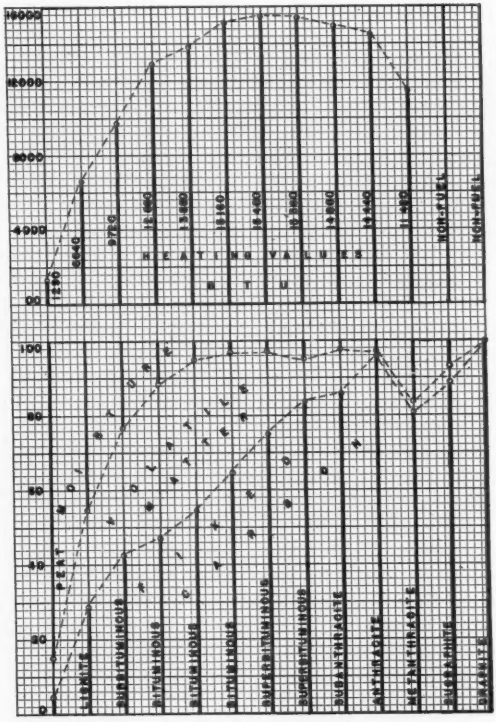

FIG. 2. Diagrams showing the proximate composition and (above), in British thermal units, the calorific values of typical members of the coal series. (After M. R. Campbell, Proc. Int. Conf. on Bituminous Coal, Pittsburgh, 1926, Fig. 1, p. 10, with addition of non-fuel residues.)

the weight percentages greatly undervalue hydrogen, the constituent that is determined quickly, easily, and with a high degree of precision. Furthermore, small differences in hydrogen con-

tent are of the first importance in determining the qualities of the successive products. This element is closely correlated, for example, with calorific values, coking qualities, and the yield of volatile products.

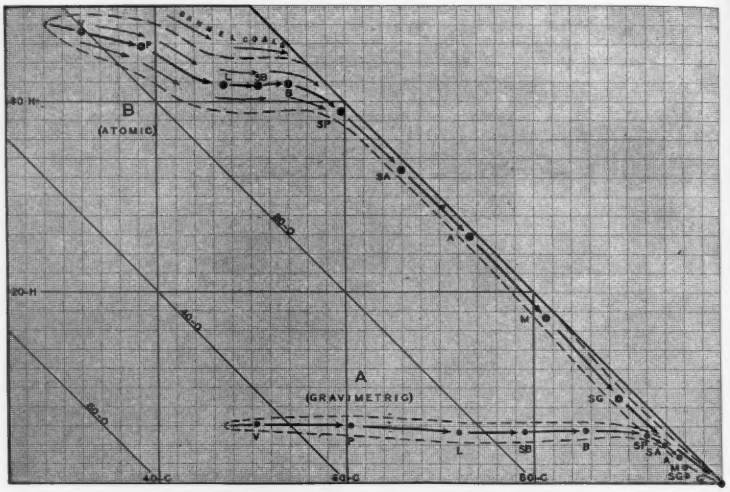

FIG. 3. Diagram showing distribution of the coal series on trilinear coördinates, on the basis of carbon, hydrogen, and oxygen content calculated to 100. (*A*) On gravimetric data. (After O. C. Ralston, U. S. Bur. Mines Tech. Paper 93, 1915.) (*B*) On atomic percentages. The initials in the "coal belt" denote: *V*, vegetal debris; *P*, peat; *L*, lignite; *SB*, subbituminous coal; *B*, bituminous; *SP*, superbituminous; *SA*, subanthracite; *A*, anthracite; *M*, metanthracite; *SG*, subgraphite; *G*, graphite.

In Graph *B*, Fig. 3, these weaknesses have been largely overcome. It is based on the atomic percentages, as given in Table I, column 4. Here it is at once apparent that the transitional "flow" from vegetal debris through the bituminous range does not follow a straight-line course. Thus, besides the great reduction in oxygen during the conversion of plant materials into peat and the lignites (browncoals), a notable drop in hydrogen also

is clearly shown. Following this there is a relative rise in hydrogen, from lignite through the bituminous group; and finally the long steep descent due to the rapid elimination of hydrogen beyond the superbituminous rank (SP). In this declivity, which follows essentially a straight course, the advanced ranks and high-carbon residues are well separated and their relationships clearly shown, in the long narrow "bottle-neck" into which all types of coal converge as age-long differences vanish. Furthermore, the metanthracites and subgraphites fall naturally into the flow-line in Graph *B*, Fig. 3, whereas in Graph *A*, on the gravimetric basis, they appear to be isolated. A striking feature of the metanthracite region is the marked reabsorption of oxygen, as the atomic percentage of hydrogen drops below 20, and the consequent diversion of the narrow channel of flow from the zero-oxygen line.

An important feature that does not appear in Fig. 3, but is clearly seen in Figs. 14 and 17, is the drastic waste of all constituents along the track from vegetal debris to lignite. In Fig. 3, hydrogen appears in gentle decline along this course, because here carbon and oxygen also are wasting rapidly and only differential losses can appear in the triangular diagram; whereas Fig. 17 shows that hydrogen is being discharged at a far greater rate in the early stages than along the steeper anthracite track in Fig. 3. In a following section of this paper it is estimated that the average losses in the first two stages alone have dissipated 50% of the original accumulation. In the long succession of changes throughout the rest of the coal series, the losses all together are equal to only about one half as much. It is also clear that, in every stage, carbon is the element that is least reduced; hence the consistent enrichment in carbon in each successive residue.

A feature of the first importance in Fig. 3 is the continuity of the coal series, without a break, from the vegetal source materials to anthracite. "Thin places" appear, it is true, where fewer analyses are available, as, for example, between vegetal debris and peat, between peat and lignite, and between bituminous and superbituminous coals. Furthermore, in the whole anthracite

range relatively few analyses appear, and in the highly metamorphic range of the metanthracites and subgraphites few examples are known; so the definite location of these ranks is largely hypothetical in the present state of knowledge. Here, wider open spaces are found, but no reason appears for questioning the actual continuity of the series through these spaces to graphite. Doubtless additional examples will be identified and analyzed from time to time in the various slate formations, the phyllites, and the crystalline schists.

TRANSFORMATION.

The Wasting Processes.

The transitional "flow" of the coal series, as shown in Fig. 3, is unidirectional, and apparently the changes are continuous. Every essential process involved is a wasting process. The external agencies, such as atmospheric oxidation and solution in the swamp waters, are actively engaged in the destruction and removal of the source materials. Also the internal changes that dominate the transformations are all degradational, thus dissipating in part the energy that was stored up by the growing plants. Possibly the coals possess within themselves the capacity for change, apart from and independent of the effects of the external forces to which they may be subjected. It has been suspected that the complex organic compounds are thus undergoing perpetual decay. The gaseous discharge of coal has been characterized as at once the evidence and the necessary result of a continuing evolution.[8] However, the importance of accelerating and retarding influences is recognized.

Concerning the essential character and the mechanism of the transitional changes almost nothing is known. The nature of the volatile products discharged is known in part, and their relative abundance may be roughly estimated. As the complex organic molecules break down eventually they pass into the simplest binary compounds of carbon, hydrogen, and oxygen, and a residue

[8] Briggs, Henry: The Evolution of Coal. Chem. and Ind., vol. 50, pp. 127–133, 1931.

of solid carbon. The compounds are fluid and may escape in liquid or gaseous form. Because of the disproportionate elimination of the several elements, the losses are marked by changes in bulk composition; also they are accompanied at every step by marked physical changes, such as darkening, compacting, hardening, and the development of joint fractures. The residues become progressively leaner in those elements that are most reduced—first oxygen, later hydrogen—and hence steadily richer in carbon, the element that is lost in smallest proportion. A constant change would give a straight-line "flow" in the ternary diagram, Fig. 3; hence the sinuous course (Graph *B*) gives positive evidence of repeated variations in either the character or the proportions of the substances discharged.

The Volatile Products.

The transitions from rank to rank in the coal series are brought about primarily by internal molecular adjustments which cause the detachment and elimination of simple volatile substances from the great unstable organic molecules that characterize the vegetal debris and the coals that are derived from them. These emanations consist almost entirely of the simplest compounds of carbon, hydrogen, and oxygen—chiefly carbon dioxide, water, and methane (Fig. 15). In smaller proportions also carbon monoxide and nitrogen are released, and sometimes traces of hydrogen disulphide and the higher hydrocarbons. From peat, lignite and the less mature coals, the oxides (water and carbon dioxide) are the preponderant substances given out, and the same products are extracted upon heating up to 100° C. In the mines these lower coals also give off more carbon dioxide than methane, and some of the mines emit no combustible gas.

The water above referred to is newly-formed water of decomposition. It is not to be confused with the original water of saturation, much of which is an essential constituent of the humic hydrogels, nor with the moisture that is held generally in capillary pores and adsorbed films on the surfaces of the coal. In nature this new water, like the expelled portions of the original satura-

tion, is added to the general body of the ground water. Hence it does not appear at the surface with the escaping gases. In large measure the same is true of the carbon dioxide, which at ordinary temperatures is soluble in water.[9] Therefore, methane is generally the dominant gas escaping from the coals, even in the lower ranks from which oxide emanations are abundant. From the higher bituminous coals and the anthracites, the volatiles escaping naturally and extracted at low temperatures contain increased proportions of methane, together with greatly reduced amounts of the oxides, water and carbon dioxide. Also, the deeper seams in many coal fields yield notably larger proportions of methane than the shallower ones (Hilt's law).

The amount of gas in a mine is no criterion of the quantity that may be extracted from the coal. The bituminous mines generally have more gas than anthracite mines, notwithstanding the fact that the anthracites yield more gas at low temperatures (up to 100° C.) than bituminous coals. Apparently the density is the controlling factor, the gases escaping more readily from the coals of lower density. How the gases are held in the body of the coal, however, whether adsorbed, occluded, dissolved, or mechanically imprisoned in the submicroscopic interstices of the humic colloids, or, on the other hand, whether and to what extent they are evolved contemporaneously from the coal substance, are questions that are still largely speculative. The large volume of gas immediately available may be mostly stored up in some manner; but the slow escape that continues through the many months of the experiments may consist in part of newly formed products.

In the following pages the effort is made to define approximately the kinds and proportions of materials that are emitted from stage to stage and to set tentative limits within which these changes take place. Owing to the lack of basic data the transi-

[9] At 30 degrees Centigrade, water dissolves 66.5 per cent of its volume of carbon dioxide. In contrast, it absorbs only 2.6 per cent of oxygen, 2.0 per cent of carbon monoxide, and 1.7 per cent of hydrogen. At this temperature methane is insoluble in water. At 20 degrees the corresponding solubilities are: Carbon dioxide 87.8; oxygen 3.1; carbon monoxide 2.3; hydrogen 1.8; and methane 1.4. (Malisoff, William, and Egloff, Gustav: Methane. Jour. Phys. Chem., vol. 22, pp. 529–575, 1918.)

tions can not be sketched in great detail, nor with full confidence in the accuracy of the results. Thus, (1) at the very source of the supply, little is known of the rate of growth of swamp forests, under the widely varied conditions of temperature and distribution of the rainfall. (2) The losses due to rotting in the air doubtless are always heavy. Under some conditions, particularly with alternating wet and dry seasons, the destructive processes may keep pace with the annual growth, so that little or no surplus accumulates. (3) The extraction of materials by solution and colloidal suspension is known to be active, and the drainage from swamps everywhere is heavily laden with organic matter; but quantitative data are lacking. (4) Oxygenated ground water, where it gains access to coal beds, may " regenerate " the insoluble humic substances and thus promote further loss of materials through solution. Where such soluble humins already exist, as in the buried peat beds and the lignites (browncoals), the water-borne oxygen may speed their decomposition into simple oxides of carbon and hydrogen; but little is known of the efficacy of such processes. (5) In the laboratory the presence of alkaline carbonates and bicarbonates, even calcium carbonate, in the water promotes the solution of humus from peat and lignite. In some fields this process is in operation, but the quantity of material removed in this manner is unknown. (6) Most important of all from the point of view of the present inquiry, both the nature and the rate of the internal disintegration, which disengages some of the constituents and brings about the transformations from rank to rank, are still largely matters of speculation. Even the knowledge of end-products is fragmental and most of it only qualitative.

The type analyses given in Table I, together with Figs. 1 and 17, show the marked enrichment in carbon with each advancing step in the series, the rapid drop in oxygen throughout the first half, and the decline of hydrogen, which is most obvious in the analyses beyond the bituminous range. Large quantities of the gases evolved, notably carbon dioxide and methane, withdraw carbon; hence it is clear that the total amount of this element also is being steadily reduced—chiefly as carbon dioxide in the earlier stages,

as methane in the later. The steady enrichment in carbon shows, however, that the other elements are being removed at a more rapid rate proportionally (Figs. 1, 2). It follows, therefore, that actually hydrogen and oxygen are being diminished even more rapidly than appears in the analyses. The losses shown in Fig. 14, Graph *A*, and in the corresponding graphs, Fig. 17, are the estimated average losses, which are believed to be very near the actual facts.

Stages of Decay.

Immediately upon the death of plants their remains are subjected to a series of complex processes of dissolution. These are particularly severe in the early stages. So far as they apply to swamp materials, as the basis of the coal series, the processes may be grouped conveniently under three heads:

(1) Rotting in the air. Primarily oxidation and apparently due in the main to the biochemical activities of fungi and bacteria.

(2) Decay under water. Apparently related to fermentation, and most probably due in great measure to anaerobic bacteria.

(3) Subterranean processes, which may be termed geochemical.

These operations overlap in some degree, particularly those of the first and second categories, which appear to be conditioned essentially on biochemical processes. Between these two also there may be repeated alternations, as the water levels fluctuate in the swamps. From the chemical point of view, the first involves changes that are due largely to external agencies, of which atmospheric oxidation is the chief. Where it runs its course unchecked, as in most forest regions, it leads to the complete destruction of all vegetal debris; hence there is no accumulating surplus. The subaqueous and subterranean changes, on the other hand, are concerned in the main with internal degenerative processes, in which the organic substances gradually step down, through a long series of complex products, to simpler compounds. This decay apparently is continuous through all stages, but it does not proceed at a uniform rate. Geological evidence points to long periods of quiescence, during which the rate of change may drop nearly, if not quite, to zero.

In part both the physical and the chemical changes may be ascribed to gravitational compaction, particularly in the conversion of vegetal debris into peat and this, in turn, into lignite and the lower bituminous coals. In the higher bituminous ranks and in the anthracites profound changes are bound up with lateral compression and the resultant stresses and rise in temperature. All phases of these compressional and thermic effects, collectively, may be termed geochemical.

Rotting in the Air.

Of all the processes of dissolution, the rotting of organic debris in the air is the most drastic. The rapid destructive changes involve immense losses of material. Accompanying the decay, and apparently responsible for it, is a vigorous growth of fungi, which penetrate all woody materials above the water level. Quickly following and accompanying these organisms are active bacteria. Furthermore, the materials are invaded and partly consumed by many kinds of insects, larvae, worms, and other animal forms. Unless arrested, these multiple attacks destroy the organic debris and return the constituent substances to their original forms of simple carbon dioxide and water. Thus carbon, hydrogen, and oxygen repeat the organic cycle over and over. Even those parts that are retained through the vast eras of the coal transformations eventually return to these simple compounds and recapitulate with infinite variations.

Some of these destructive changes may be independent of the activities of the organisms, but in the main they are doubtless biochemical, and in their initial stages perhaps they are essentially so. Where the level of the swamp water fluctuates, it alternately submerges and then exposes to the air large quantities of fallen plant debris, thus interrupting the rotting process from time to time, by shutting off the supply of free oxygen and substituting the less severe operations under water.

In the accumulating debris at the surface of the swamp, rotting is practically continuous, and great losses must be attributed to it. The rate of destruction must vary from place to place, how-

ever, with many local conditions, and also from time to time, with seasonal changes and the slower secular variations. Furthermore, there is wide variation in the susceptibility of the materials, and hence the process is highly selective. Soft tissues yield more readily than the firm wood. Timbers that are free from toxic and protecting products rot quickly; those that are rich in tannins or resins are more resistant. Trees of the latter types were more abundant in the coal-forming swamps of Cretaceous and Tertiary times than in those of the earlier periods. This doubtless explains, in part at least, the greater abundance of wood in these later coals and lignites. Indirectly, atmospheric oxidation affects even the materials that have become submerged in the swamps, since the substances in solution and colloidal suspension are exposed continuously to oxidation at the surface of the water.

Chemically, the decay of wood is a process of degeneration, the complex compounds disengaging the simple volatile emanations, carbon dioxide, water, methane, and hydrogen, and the final products being carbon dioxide and water. In swamps of vigorous growth the net result is the destruction and removal of most of the celluloses, whereas the greater part of the lignin, with little change in bulk composition, is stepped down into the humic complex and preserved as the chief constituent of the common coals. It is estimated that the processes of decay destroy one-half of the original plant accumulations during their conversion into peat and lignite. Nevertheless, as David White [10] has pointed out, the amount of residual woody tissue found in most coals justifies the belief that the decomposition of organic refuse was less complete in the great coal-making swamps than in the average present-day peat. The rapid growth of the swamp forest, and hence the rapid falling and accumulation of debris, covered and protected the rotting materials from long exposure to the air and weighed them down rapidly beneath the surface of the water. In the densely forested inland swamp of southeastern Sumatra, for example, the rate of growth is eight to ten times that of the

[10] White, David, and Thiessen, Reinhardt: The Origin of Coal. U. S. Bur. Mines, Bull. 38, p. 86, 1913.

temperate zones. The forest reproduces itself in seven years, and trees grow to the height of 100 feet in nine years.

Decay Under Water.

Since coal is a product of the arrested decay of land plants, the most vital conditions for its formation are those that arrest the decay. Submergence ends abruptly the destructive rotting stage. It shuts off the supply of atmospheric oxygen and exterminates the fungi, the aerobic bacteria, and the accompanying assemblage of animal forms. In the water, decay proceeds at a greatly reduced rate, accompanied by the activity of the anaërobic bacteria. The biochemical processes that dominate depend on the activity of the enzymes secreted by the microörganisms. These forms are vigorously active in the surface waters of the swamp generally, and Thiessen [11] has reported the presence of living bacteria in peat to the depth of 30 feet. They may play a part in the progressive humification and carbonization of the peat in depth.

The anaërobic bacteria obtain their oxygen from compounds that are present in their environment; hence they are active agents in the reduction of saturated organic matter and of similar materials that accumulate as fine oozes in the open waters. Also, besides oxygen, they take away carbon, hydrogen, nitrogen, sulphur, and phosphorus, but in smaller amounts proportionally. The net results are the diminution of the total quantity of organic matter and a decrease in the content of oxygen, nitrogen, sulphur, and phosphorus in the residual materials, with the corresponding relative increase in the carbon content. Hydrogen is removed only in sufficient quantity to maintain the same proportion in the residue as in the original materials. Hence inspection of the analyses is apt to give the impression that no hydrogen has been lost (compare Figs. 1 and 17).

As the sources of energy are gradually consumed and the toxic products of metabolism accumulate in the water, the numbers and activity of the bacteria decline, especially in the stagnant

[11] Thiessen, Reinhardt: Some Recent Developments on the Constitution of Coal. Proc. Second Int. Conf. on Bituminous Coal, Pittsburgh, 1928, vol. 1, pp. 739, 740. See also Trans. Amer. Inst. Min. Eng., vol. 88, Coal Division, p. 436, 1930.

depths of the peat, even though oxygen-bearing substances are present. Generally it has been assumed that the concentration of poisonous waste products exterminates the microörganisms in the deeper peats. Rainfall and drainage waters, however, tend to dilute the solutions, particularly in the shallower depths, and hence to promote the activity of the bacteria. On the other hand, the evolution of gases from coals of all ranks and types may be due in part to the continued breaking down of unstable substances, possibly without the aid of bacteria, into the simple products, methane, carbon dioxide, and water. Just where, in these progressive changes, the biochemical processes cease and give place to the geochemical, which are activated through the inorganic agencies of temperature and pressure, has not been definitely determined. Most of the activities of the organisms seem to end with the open peat stage.

The violence of rotting in the air and, in lesser degree, also that of subaqueous fermentation, breaks down the tissues and destroys the cells in many of the plant structures. The process is selective, however, the hardest, in general, being the most resistant. Where the action is long continued and all woody materials destroyed, only the most resistant cuticles, resins, waxes, and spore coats remain intact. In peat and the coals are found residues from all degrees of decomposition and disintegration, giving all gradations of mingled humic products with cells from macerated tissues and fragments of fibrous and woody parts in every stage of decay.

Owing to the active elimination of volatile oxides from the submerged materials, peat is markedly lower in oxygen content than were the original plant substances. The swamp waters and the outflowing drainage are heavily charged with humic products in tea-colored to coffee-colored solutions. These substances are subject to continuous oxidation to water and carbon dioxide at the surface of the swamp. This process reduces the concentration and thus promotes progressive solution and oxidation of additional quantities of the same materials. The total losses attributable to this cause may be considerable, but the data required for quantitative estimates are lacking.

Subterranean Changes.

Spontaneous Degeneration?—In contrast with the destructive process of rotting in the air, or even the retarded fermentation in water, the conversion of peat into lignite and of this, in turn, into the coals of higher rank is a slow and gentle operation. Whether the bacteria or their enzymes retain any appreciable activity in the greater depths of peat and under the cover of accumulating sediments is a question that still awaits a definite answer. The dissolution of tissues and the destruction of cells ends with the maturing stages of peat or soon thereafter, for the original structures that are preserved in peat persist in the coals of every rank and type. With the exception of local mechanical crushing, these cells suffer only progressive changes in composition and, with the continued separation of volatile materials, they shrink and collapse with the compression of the mass, its consolidation into coal, and its continued condensation throughout the higher ranks.

Nevertheless, the decomposition that was inaugurated with the biochemical action above the surface of the swamp and was continued at a reduced rate beneath its waters has been perpetuated in geologic time through all of the stages of coal until, in average anthracite, only 57% of the original carbon, 13.5% of the hydrogen, and 1.2% of the oxygen remain. For bituminous coal the corresponding figures are: 63% carbon, 33% hydrogen, and 7.7% oxygen (Fig. 17). Moreover, the products discharged are largely the same at every stage, but with a marked increase in the proportion of methane and a corresponding drop in the oxides (water and carbon dioxide), beyond the bituminous range (Fig. 15). Apparently the activities of the organisms are essential in starting this long chain of degenerative operations; but after the earliest stages other agencies stimulate the process, apparently with little or no biochemical aid.

Through the long subterranean stages, the elimination of water in great quantities from the humic colloids, together with the release of simple volatile compounds of carbon, hydrogen, and oxygen, continues from the coals of every rank and variety. The

causes are unknown. The process suggests the gradual, spontaneous running down of an unstable system, the equilibrium of which was upset perhaps by the violent biochemical attacks to which it was subjected in its early history. Under the pressure of overlying strata up to a mile or more in thickness, and acting through time that is measured in geologic eras, much has been accomplished, apparently at very moderate temperatures. Furthermore, the slow deliberate changes have been speeded up at times of active diastrophism, when subsurface temperatures rise and vast lateral thrusts come into play. "In fact, the essential changes, including loading, progressive dehydration, compression, induration, jointing, devolatilization, and refinement of cleavage, with gradual losses of carbon, hydrogen, and oxygen, which characterize progressive carbonization, are now in progress in most coal fields." [12]

Dynamic and Thermic Influences.—That spontaneous decay has not been the dominant factor in the making of the higher coals is shown by their geologic relations. If this were so, the ancient coals should all be far advanced. The lignites of Lower Carboniferous (Mississippian) age in the Moscow basin and of Liassic age in Hungary are conspicuous examples of the contrary. Furthermore, if time and spontaneous degeneration controlled, the widely observed correspondence between the rank of coal and its diastrophic history would scarcely be possible. The stresses and strains to which the coals and their accompanying strata have been subjected, together with the resultant joint fractures, fissures, flowage, and temperature changes, undoubtedly have determined in large measure the status attained by many coal deposits.

Concerning the evaluation of the various factors involved there is wide difference of opinion. David White [13] attaches great importance to horizontal thrust pressures, minimizing the influence of loading and depth of burial. On the other hand, George

[12] White, David: Progressive Regional Carbonization of Coal. Trans. Amer. Inst. Min. Eng., vol. 71, pp. 253, 254, 1925.

[13] U. S. Bur. Mines, Bull. 38, 1913; Trans. Amer. Inst. Min. Eng., vol. 71, p. 253, 1928; Proc. Nat. Acad. Sci., vol. 14, p. 5, 1928.

A. Hickling [14] considers depth of cover and resultant rise in temperature the most important factors. Depth also is held essential to effective diastrophism. Folding and faulting are deemed important to the extent that they increase the thickness of overlying strata. White attributes effective rise in temperature to granular and molecular readjustments under thrust pressures; Hickling doubts the thermal efficacy of such movements except as they add to the depth of cover. Campbell [15] has stressed the importance of gravitational compaction and the development of joint fractures, thus affording ready means of escape for the discharged volatile substances.

Gravitational compression, due to the weight of the accumulating vegetal debris, the water of saturation, and eventually the overburden of sediment, is important in the early stages, when it operates alone or with slight rise of isogeotherms, in the compaction of materials and the resultant reduction of the water content. Chemically, gravitation seems to influence in considerable degree the downward course of change in unstable materials. Evidence of this is seen in Hilt's law of the rise in rank with depth, the validity of which has been verified in many coal fields. The deeper beds show a progressive enrichment in carbon and a corresponding decline in hydrogen and volatile products. However, it has not been determined to what extent these effects may be attributed to differences in temperature.

On the other hand, during periods of orogenic disturbance there are vast lateral thrusts, accompanied by marked and long-continued increments of heat. Here also the depth of cover is vital for both pressure and temperature. In regions that have been stable through long periods the geothermal gradient drops to one degree, Fahrenheit, in one hundred feet (one degree, C., in fifty-five meters), or even lower; while in belts of active disturbance it may rise to one degree in twenty feet (one degree, C., in eleven meters). Under the latter conditions slow distillation may proceed at moderate depths for relatively long periods of

[14] Can. Min. Jour., vol. 52, p. 428, 1931; Jour. Inst. Fuel, vol. 5, p. 318, 1932; Colliery Guardian, vol. 144, p. 401, 1932.

[15] Campbell, M. R.: Econ. Geol., vol. 1, p. 26, 1905–6; vol. 25, p. 675, 1930.

time, and such conditions may be induced repeatedly in the course of an involved orogenic history.[16] David White [17] estimates that most coals have been buried not more than 7000 feet nor subjected to temperatures exceeding 300° C. Also at 300° the constituents of coal-tar distillation begin to appear. Since these materials are not found normally in the coals, the temperature, in all probability, has not been as high as 300°. Hickling [18] estimates, on the basis of the depth of burial, that temperatures above 200° have not acted on the coals. Zetsche and Kälin,[19] after experiments with isolated constituents of lignites and coals, conclude that the bituminous coals must have been formed at temperatures below 200° C., and probably little, if any, above 100°. White estimates that anthracite has been recemented under the influence of thrust pressures at temperatures much below 450°, which is about the average temperature of fusion of the bituminous coals. Under the low temperatures and static pressures of the long quiescent periods the rate of spontaneous change doubtless becomes exceedingly slow.

While recognizing the accelerating effects of pressure in the development of the coals, Henry M. Briggs [20] also cites evidence of retarding influences to account for the lignitic deposits of the Moscow basin, coal pebbles of various ranks in the Carboniferous conglomerates of England, lignite lenses in the shales of the same coal measures, the higher volatile content in Welsh anthracites

[16] Besides intense pressures and the rise in temperature, possibly other factors also enter into the energy complex that speeds up the transformation of coal in regions of dynamic disturbance. Suggestive results obtained by the use of supersonic vibrations have been reported by Professor A. Szent-Györgyi, of the University of Szeged, Hungary. (Nature, vol. 131, p. 278, 1933.) With a quartz plate vibrating 723,000 times per second, cane sugar is said to break down into simple monosaccharides, starch into dextrins, and other highly polymerized compounds, such as gum arabic and gelatine, are depolymerized, as indicated by the drop in viscosity. The great, loosely-bound molecules seem to be shaken down, like frail buildings in an earthquake. Possibly the unstable humins also may prove to be sensitive to high-frequency vibrations, and some of the seismic energy of growing mountain ranges may well take this form.

[17] Proc. Nat. Acad. Sci., vol. 14, p. 5, 1928.

[18] Jour. Inst. Fuel, vol. 5, p. 328, 1932.

[19] Helv. Chim Acta, vol. 15, p. 675, 1932.

[20] Chem. and Ind., vol. 50, p. 127, 1931.

of high ash and in thin bands of impure coal, some of which are more than double that of the clean coal. The impurities apparently are regarded as a hindrance to the transformation. Possibly, however, the cause may be mechanical rather than chemical, since the dull impure coals are not so well "cleated," or jointed, as the pure anthracites beneath. The semiplastic, incompetent beds have failed to develop the full quota of joint cracks, which would afford a means of rapid escape for the discharged volatiles; also they have probably served in a measure to relieve the stresses by plastic flowage, and thus have shielded the enclosed and accompanying coals from the full effects of the orogenic activity.

In the great coal fields the continuous beds, although retaining their type characteristics, change progressively to higher rank as they are followed into regions of greater disturbance, but they hold the same relative position in the "coal belt" of Fig. 3. The high-hydrogen and low-hydrogen coals persist above and below the central axis of "flow," respectively, and advance along lines parallel to this axis to the end of the bituminous range. Hence, the coal belt in this region consists of a multitude of parallel linear series. With the depletion of hydrogen at the transition to the anthracites, the distinctions that depend chiefly on the hydrogen content quickly disappear. This applies not only to differences within the common humus coals, but also to the distinctions between these, on the one hand, and the cannels, on the other.

Ground Waters.—Ground waters in some regions find free access to the coal seams, and a wide variety of artesian structures may give the pressure required for active movement. Aerated waters may thus lead to losses of carbon and hydrogen from the coals through their oxidation to carbon dioxide (or monoxide) and water; and circulating ground water would remove these products of decomposition. The "regeneration" of soluble humins in the higher coals is also possible under such conditions. Furthermore, in many semi-arid regions the waters carry alkaline carbonates and bicarbonates in solution. Even in humid climates, calcium carbonate may be present in effective proportions

for the solution of humic substances. Pishel[21] has described the lignite fields of Fort Berthold Indian Reservation, North Dakota, where the waters of hundreds of springs are stained brown with substances dissolved from the coal. Similar conditions in Alberta and Saskatchewan have been observed by Jones.[22] The latter also suggests that the base exchange of clays, as demonstrated by McKenzie Taylor,[23] may be important in the solution of coals by ground waters that have been made alkaline by released sodium.

The dominance of carbon dioxide in the natural gases of some coal and oil fields may be attributable in part to the influence of oxygenated waters. Also the greater abundance of carbon dioxide from the shallower coal seams, in contrast with that of methane from the deeper ones, may be due in some measure to the same cause. The high proportion of nitrogen in some natural gas has been ascribed to aerated waters, the oxygen presumably having been consumed in the oxidation of organic materials.

The humic mixtures have approximately the bulk composition of average peat; hence the losses from peat due to the solution and removal of portions of the humus may produce little change in the composition of the residue. On the other hand, the extraction of humus from lignite and the coals of higher rank would remove hydrogen and oxygen at a greater rate proportionally than carbon. Owing to the difficult regeneration and solution of such materials in the bituminous coals, and especially in anthracite, these higher members of the series probably seldom suffer serious losses from this cause.

Graphic Examination of Chemical Changes.

Trial and Error.—On the basis of various assumptions concerning the nature of the discharged substances, approximate limits may be set within which, in all probability, the transformations in the coal series generally take place. Such limits (Figs.

[21] Pishel, M. A.: U. S. Geol. Surv. Bull. 471, pp. 177, 178, 1912.

[22] Jones, I. W.: ECON. GEOL., vol. 23, pp. 376–379, 1928.

[23] Taylor, E. McKenzie: Nature, vol. 120, pp. 448, 449, 1927; vol. 121, pp. 789, 790, 1928; Fuel, vol. 7 (5), pp. 230–238, 1928.

4 to 13) have been found by the tedious and laborious method of trial and error, and the results have been checked by calculation. Obviously their value must depend on the validity of the assumptions on which they are based.

The method may be illustrated by reference to Fig. 4, in which Graph *V* represents the ultimate atomic composition of average wood, as an approximation to the forest debris that constitutes the principal raw material of coal. Graph *P* shows the corresponding composition of average peat.[24] All of the transition graphs are constructed on a logarithmic vertical scale; hence any graph may be shifted to any other position, above or below, without altering the relative proportions of the elements, so long as it is kept parallel to its original position. Thus Graphs *P*, *P*-1, *P*-2, *P*-3, Fig. 4, all represent the same average composition of peat. Similarly, Graphs *L*, *L*-1, *L*-2, *L*-3, *L*-4, Fig. 5, are identical representations of average lignite; and so on through the entire coal series, Figs. 4 to 13.

The unequal losses that give rise to the successive ranks of coal yield a progressively higher proportion of carbon in the residues; hence the carbon in Graph *P*, Fig. 4, is represented by a point above that of Graph *V*. However, since all the elements have suffered loss, and the increase in carbon is only relative, a place must be found for Graph *P* somewhere below Graph *V*, in order to represent peat as a residual product of plant materials.

Using the method of experimental trials, Graph *P*, Fig. 4, was moved into various parallel positions below Graph *V*, in the effort to determine: (1) the minimum losses of the separate elements whereby the conversion of vegetal debris into peat might be accomplished; (2) similar minimum losses on the assumption that the elements are disengaged in the proportions of the definite compounds that are known to be given off; (3) the maximum losses consistent with such transformation; and (4) the theoretical maximum with discharge of carbon monoxide, instead of

[24] Atomic ratios of carbon, hydrogen, and oxygen, as given in Table I, are used throughout. For convenience the decimal point is omitted, which is equivalent to multiplying by 100.

the dioxide. If such limits can be established for all combinations of the volatile products that escape, and if it be assumed that the transformations are due to internal changes alone, it is evident that the actual course of the conversion in any given case must lie somewhere within the boundaries thus set.

Under the conditions assumed in (2), (3), and (4), the binary compounds, water, carbon dioxide, and methane, are considered in successive pairs: H_2O, CO_2; H_2O, CH_4; CO_2, CH_4. In the last of these, also, CO is substituted for CO_2, thus adding another pair. Assuming that the conversions may be brought about through the separation of these substances, each pair presents a problem that is capable of a definite solution. Thus, in moving the graphs up and down on the scale, in Figs. 4 to 13, it is possible to test out various positions until one is found that meets each of the particular requirements in turn.

However, if a third member be introduced into any of the groups of substances discharged, the problem becomes indefinite. and the conditions can be met by any one of a considerable number of combinations. In the varied natural circumstances doubtless similar variations occur in the products given out. Tentative limits have been set by considering the emanations in pairs. The natural transitions may lie in various positions between these limits and may involve the simultaneous or successive liberation of three or more of these products.

Minimum Losses.—The consistent rise in the relative carbon content from rank to rank, as shown by analyses, demonstrates the fact that this element at every stage has suffered less reduction, proportionally, than the other constituents. Hence the possibilities for establishing the upper and lower limits of loss may be explored under the various assumptions that follow:

(1) Minimum loss with separation of hydrogen and oxygen, all of the carbon being retained.

Inspection of Graphs *V* and *P*, Fig. 4, for example, shows that the losses incurred in the conversion of vegetal debris into peat would be at the absolute minimum if the scale value for carbon (504) in Graph *P* were lowered until it coincides with the carbon

value (421) in Graph *V*.[25] Calling the new position of the peat curve *P*-1, it is obvious that the intervals between Graphs *P*-1 and *V*, Fig. 4, measure the minimum amounts of hydrogen and oxygen that must be eliminated in order to transform the residue into peat. This procedure, from rank to rank throughout the coal series (Graphs *P*-1, Fig. 4, *L*-1, Fig. 5, etc.), does not at any stage yield hydrogen and oxygen in the proportions required for water. In the first half of the series, from forest debris to bituminous coal, there is a constant excess of oxygen; beyond the bituminous range there is a similar excess of hydrogen, which steadily increases as far as metanthracite.

To the extent that these elements combined as water the product would merge with the ground water. The excess of oxygen or hydrogen would appear in the gaseous emanation, except to such extent as it might be dissolved in the ground water or might combine with extraneous materials. Free oxygen, such as indicated under this assumption through the first half of the coal series, is sometimes observed in small amounts. In view of the abundance of unstable organic compounds with strong affinity for oxygen, the escape of this element uncombined in any considerable quantities seems highly improbable. A little hydrogen also is sometimes found among the gases that escape from peat bogs and swamps. Its origin may be due in part to the oxidation of hydrogen disulphide rather than direct elimination from peat. Free hydrogen is not a recognized natural product of the higher coals, and its escape in abundance throughout the anthracite range quite certainly does not occur. Therefore, although the minimum losses under this assumption have been determined for purposes of comparison throughout the coal series, it does not seem at all probable that the actual transformations occur in this manner.

(2) Minimum loss with elimination of simple compounds—water and carbon dioxide; water and methane.

On the assumption that the elements shall be discharged in the

[25] Trial positions of the graphs on the logarithmic scales may be established most conveniently by the use of dividers, with which equal distances, and hence proportional values, are set off on the respective scales for carbon, hydrogen, and oxygen. The method is quicker, more exact, and less liable to accidental error than the use of triangles or parallel ruler.

form of the definite compounds that are known to escape from the coals, the minimum loss will be incurred when the hydrogen and oxygen unite as far as possible to form water. Only the unbalanced excess of oxygen (in the first half of the series) or of hydrogen (in the second half) will then require carbon for the formation of carbon dioxide or methane. The abstraction of the requisite carbon increases, in turn, the proportional amounts of hydrogen and oxygen that must be released. Graph *P-2*, Fig. 4, marks this new position of the peat curve. The newly-formed water disappears in the ground water, and a portion, or even all, of the carbon dioxide may go into solution, particularly where circulation renews the supply of water. Therefore changes in this manner would probably yield little, if any, volatile emanation.

Small differences appear between the results under conditions (1) and (2) above, as shown in the successive charts, Figs. 4 to 13. Apart from the objections to (1) above on chemical grounds, the common observation that the disengaged products appear chiefly in the form of definite binary compounds points to the greater probability that the changes designated under number (2) will actually occur. Hence it may safely be assumed that (2) rather than (1) approximates closely the minimum losses incurred in nature. This limit is marked by Graph *P-2*, Fig. 4, and by the corresponding curves (*L-2*, *SB-2*, *B-2*, etc.) in the succeeding stages, as shown in Figs. 4 to 13. Attempts to reduce further the losses under (2), by raising the Graphs *P-2*, *L-2*, etc., to higher positions, are found to yield in every case insufficient carbon to unite with the excess of oxygen or hydrogen.

Maximum Losses.—Losses in excess of those under (1) and (2) above will be incurred under conditions that withdraw greater proportions of carbon. The two combinations that follow produce this result.

(3) Maximum loss with evolution of methane and carbon dioxide.

Increased losses must result under conditions that prevent the released hydrogen and oxygen from combining as water, and lead instead to their union with carbon, as methane and carbon

dioxide. Graph *P*-3, Fig. 4, and the corresponding Graphs, *L*-3. *SB*-3, etc., in Figs. 4 to 13, mark the positions that were found to yield these results. If these graphs are dropped lower, in the effort to increase still further the losses incurred, they yield an excess of carbon. Since this element can not escape in the free state, the various graphs with the number 3 mark the actual maxima under the conditions assumed.

(4) Maximum loss with discharge of methane and carbon monoxide.

The losses would attain a higher maximum, and hence the minimum residues would remain as coal in the successive ranks, if the conditions produced the theoretical maximum of carbon monoxide, instead of the dioxide. In the case of vegetal debris, owing to its high content of oxygen, no residue whatsoever would be left as peat; hence in Fig. 4 there is no Graph *P*-4. In the later stages, however, as shown in Figures 5 to 13, graphs bearing the number 4 mark these theoretical maximum losses and minimum residues. In the conversion of peat into lignite, Fig. 5, owing to the abundance of oxygen present, there is a wide gap between Graphs *L*-3 and *L*-4. Beyond lignite, however, the successive graphs numbered 3 and 4 lie very close together; hence there is little choice between them as markers of the maximum losses that may be incurred in the successive transformations.

Experience indicates that carbon monoxide constitutes but a small proportion of the volatile emanations of the coals. From the data at hand, however, it is not possible to judge how nearly the theoretical maximum may be approached in nature. In general, the occurrence of the monoxide seems to fall far short of this limit, and since this gas is only slightly soluble in water it can not be assumed to disappear in the ground water. It seems safe to conclude, therefore, that the actual transitions seldom take place in this manner, if at all. The maximum losses in nature probably exceed but little the values obtained under (3) above and represented in the charts by *P*-3, *L*-3, etc., Figs. 4 to 13.

Beyond lignite, Figs. 6 to 13, it will be observed that the four graphs that bear the numerals 1, 2, 3, and 4 and mark the respective high and low losses under the various conditions assumed,

all lie very close together. Hence the total range of possible variations among the limits thus set is very slight. Only in the first two stages—vegetal debris to peat and peat to lignite—are wide variations in the losses possible, under the conditions assumed. This conclusion is further sustained by Fig. 14, which shows the heavy losses of mass in these early stages, and by Fig. 17, in which the atomic losses are shown separately for the elements, carbon, hydrogen, and oxygen.

Of the four assumptions discussed in the preceding paragraphs, (1) is regarded as highly improbable, if not impossible, on chemical grounds. Number (4) also is given little weight, since carbon monoxide is found as only a minor constituent in the coal gases. On the other hand, (2) and (3) are given great weight. The products assumed (carbon dioxide, methane, and water) are abundant exhalations of the coals. Therefore, the actual minimum of losses and maximum of residual coals are denoted, at least very closely, by the conditions designated under (2) above and the corresponding graphs (*P*-2, *L*-2, etc.) in Figs. 4 to 13. Generally, carbon monoxide is found in small proportions, hence the maximum losses probably are but little greater than the limits set by (3) above and the graphs with corresponding number (*P*-3, *L*-3, etc.).

Values about midway between (2) and (3), therefore, may be assumed to mark approximately the average course of transformational changes throughout the coal series. Such approximate averages, smoothed to a curve, are represented on the gravimetric basis in Fig. 14. Corresponding atomic values for the separate elements are shown in Fig. 17. Transitions that follow an intermediate course between (2) and (3) would involve the expulsion of the three products, water, carbon dioxide, and methane. Minor amounts of carbon monoxide would generally be expected, with occasional traces of the higher hydrocarbons. From minor constituents that are omitted from the "pure coal" values in Table I would come hydrogen disulphide and nitrogen —both generally in small proportions.

External Reactions.—The foregoing discussion is based on the assumption that the transitions in bulk composition from rank

to rank are brought about solely through internal adjustments which result in progressive devolatilization. It is necessary to note, however, the tenuous nature of the established knowledge in this field. Apparently the humins are both the dominant and the most sensitive constituents of the coals; hence in the light of present understanding it seems reasonable to suppose that the gradual changes in their constitution are responsible, in large part at least, for the transformations. No external agents are known to enter into the process.

Nevertheless, it is conceivable that some reactions with other substances may take place, and until conditions are better understood such possibility can not be entirely ignored. Thus, water is present in abundance at every stage, from the swamp jungle to metanthracite and subgraphite. With advancing rank and increasing density, the elimination of the moisture that is held intimately within the coal substance is never quite completed. Possibly the water that disappears from stage to stage may not be wholly expelled in the sense of being driven out as such. May not some of it enter into chemical union with constituents of the coal or with elements that are disengaged from the unstable molecules? If its elements could be linked with carbon, to form methane and carbon dioxide, the losses of this constituent would be increased in the ratio of one carbon atom to one molecule of water; thus, $2H_2O + 2C = CH_4 + CO_2$. The loss of carbon would require the further discharge of hydrogen and oxygen in proportional amounts. It is conceivable that such reactions might proceed to the complete destruction of the coal; hence no limit can be set for the losses that might be incurred.

In general it may be assumed that if the coals are capable of uniting or otherwise reacting chemically with water, there must be some limiting condition or principle that restricts the process within narrow bounds, otherwise the coal seams would have vanished long ago.

Calculation of Losses.

As noted, the limiting losses incurred during the conversion of the coals from rank to rank, under the four assumptions enu-

merated on a preceding page, were worked out first by trial, with the aid of semi-logarithmic graphs, and the results were afterward checked by calculation.

Under number (1), which assumes the minimum losses of hydrogen and oxygen, with the conservation of all of the original carbon, no experimental trials are required. There is only one possible position for the curve of the higher rank; namely, that which brings its carbon value into coincidence with that of the lower rank from which it is derived. Similarly, in calculation, the two carbon values are equalized and the hydrogen and oxygen values of the higher rank are lowered proportionally. Only simple proportion is involved, as illustrated on the following pages.

For the calculations under the assumptions (2), (3), and (4), involving the solution of three simultaneous equations, an adaptation of Bischof's [26] method and the variation employed by J. F. Hoffmann [27] has been used. As noted in connection with the method of trial and error, the problems yield definite results when the exhalation products are considered in pairs, but become indefinite and capable of several solutions when a third product is evolved. The calculated results under conditions (2), (3), and (4) agree with those obtained by trial, within the limits of error of slide-rule computation and the avoidance, in general, of fractional atoms and molecules.

(To be concluded in the next number.)

[26] Elements of Chemical and Physical Geology, London, 1854, vol. 1, p. 275.

[27] Beitr. Geophys. (Gerlands), vol. 7, p. 327, 1905.

Bischof calculated the losses under certain conditions for the derivation of lignite, browncoal, bituminous coal, and anthracite directly from wood; also asphalt and other carbonaceous substances that are no longer regarded as related to the coal series. Hoffmann is concerned chiefly with a theory of origin, in which calorific values and the heat balance are emphasized. Neither considered the problem of limits within which the changes take place nor undertook to follow the transformations step by step through the coal series. Bischof observed that the maximum amount of carbon was lost when the transition was brought about through the release of carbon dioxide and methane, and the minimum of carbon, when carbon dioxide and water were discharged. He also noted that the latter method could not be applied to anthracite.

STRUCTURAL HISTORY OF THE FRACTURE SYSTEMS AT GRASS VALLEY, CALIFORNIA.[1]

W. D. JOHNSTON, JR., AND ERNST CLOOS.

CONTENTS.

Introduction 39
Field work and acknowledgments 40
The problem 40
The evidence 40
The granodiorite 41
Dikes 44
The vein fractures 44
The crossings 46
Evidence for the sequence of crossings, dikes, and veins 48
The synthesis 51
Previous views 51
The plastic stage 51
The rigid stage 52
Summary 53

INTRODUCTION.

GOLD was discovered in the quartz veins of the Grass Valley district, in northern California, in 1850, and mining has continued up to the present day. Lindgren's reports[2] on the district were published in 1896, and Howe's paper[3] in 1924. Various notes on mining development have appeared from time to time in the technical press and in publications of the California Division of Mines,[4] and recently Knaebel[5] presented a mineralogical study of the fissure fillings of the district.

[1] Published by permission of the Director, U. S. Geological Survey.

[2] Lindgren, Waldemar: The Gold-quartz Veins of Nevada City and Grass Valley Districts, Calif. U. S. Geol. Survey, 17th Ann. Rept., pt. 2, pp. 1–262, 1896. U. S. Geol. Survey, Geol. Atlas, Nevada City Special folio (No. 29), 1896.

[3] Howe, Ernest: The Gold Ores of Grass Valley, Calif. ECON. GEOL., vol. 19, pp. 595–619, 1924.

[4] MacBoyle, Errol: Mines and Mineral Resources of Nevada County. Calif. State Mining Bureau, Division of Mines, 1919. Logan, C. A.: Nevada County. Division of Mines, Mining in California, vol. 26, pp. 90–137, 1930.

[5] Knaebel, John B.: The Veins and Crossings of the Grass Valley District, Calif. ECON. GEOL., vol. 26, pp. 375–398, 1931.

Field Work and Acknowledgments.—In 1930 the U. S. Geological Survey began a study of the deeper workings of the district, and Johnston was assigned to that project. During the summers of 1930 and 1931 he was ably assisted in the field by R. L. Loofbourow. In the calendar years 1931 and 1932 Cloos spent twelve months in the field studying the general structural relations of the intrusives of the Sierra Nevada, including several weeks underground in the Empire-Star mines.

The writers desire to express their indebtedness to the staff of the Empire-Star Mines Co., particularly to Messrs. W. A. Simkins, F. W. Nobs, A. F. Duggleby, and John Mann, who aided their work in every possible way; to Leland Wincapaw of the Golden Center mine; and to A. B. Foote.

The Problem.—Of the many geological problems presented by the district, perhaps the one of most general interest is the origin and structural history of the vein fractures. Ample opportunity for their study is afforded by the extensive mine workings—the result of over 80 years of active mining—which follow the veins to a vertical depth of 3700 feet beneath the surface and for over two miles along their strikes.

The discussion of such a problem, involving the hypothetical reconstruction of past events, falls naturally into two divisions: (1) the evidence which may actually be observed, and (2) the synthesis of the structural picture. Such a presentation is here given.

THE EVIDENCE.

Grass Valley (Fig. 1) is on the western slope of the Sierra Nevada at an altitude of 2500 feet. The salient geological feature of the district (Fig. 2) is a body of granodiorite 5 miles long from north to south and one-half to 2 miles wide, which invades a complex of older sedimentary, metamorphic, and igneous rocks. Complementary dikes that mostly strike northeast cut the granodiorite and extend into the adjoining rocks. Fissure systems of two general kinds occur, the vein fractures and the "crossings." Most of the vein fractures strike parallel to the intrusive contacts, have dips that range between 10° and 70°, with an

average of 35°, and are generally filled with quartz. The crossings are vertical or steeply dipping fissures that strike northeast and are commonly without quartz filling.

The Granodiorite.—The granodiorite body is essentially homogeneous in character. Chemically and mineralogically it is similar to the large intrusive body at Nevada City, although separated

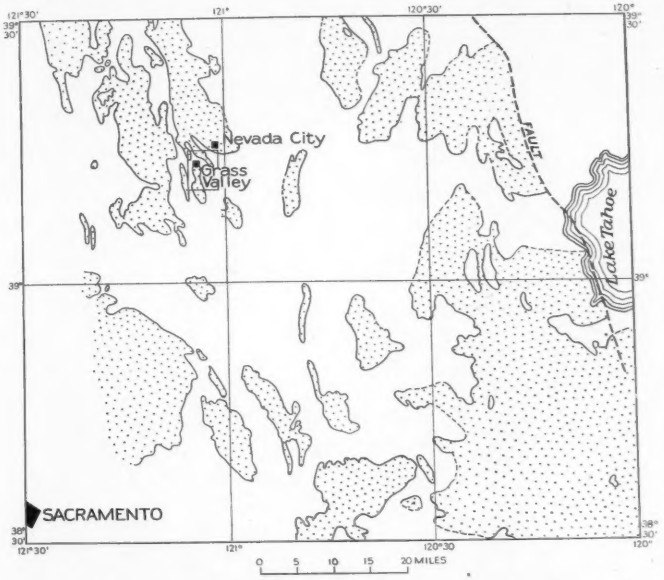

FIG. 1. Index map showing intrusive masses in the northern Sierra Nevada Mountains and the location of Grass Valley. Compiled from folios of the Geologic Atlas of the United States.

from it at the surface by two miles of older rocks. To the depth exposed by mine workings, the walls of the Grass Valley intrusive flare downward, as shown in Fig. 3. The contacts of the granodiorite with the adjoining rocks are commonly so sharp that both rocks, in their usual facies, can be represented by a single hand specimen. Inclusions of the older rocks in the

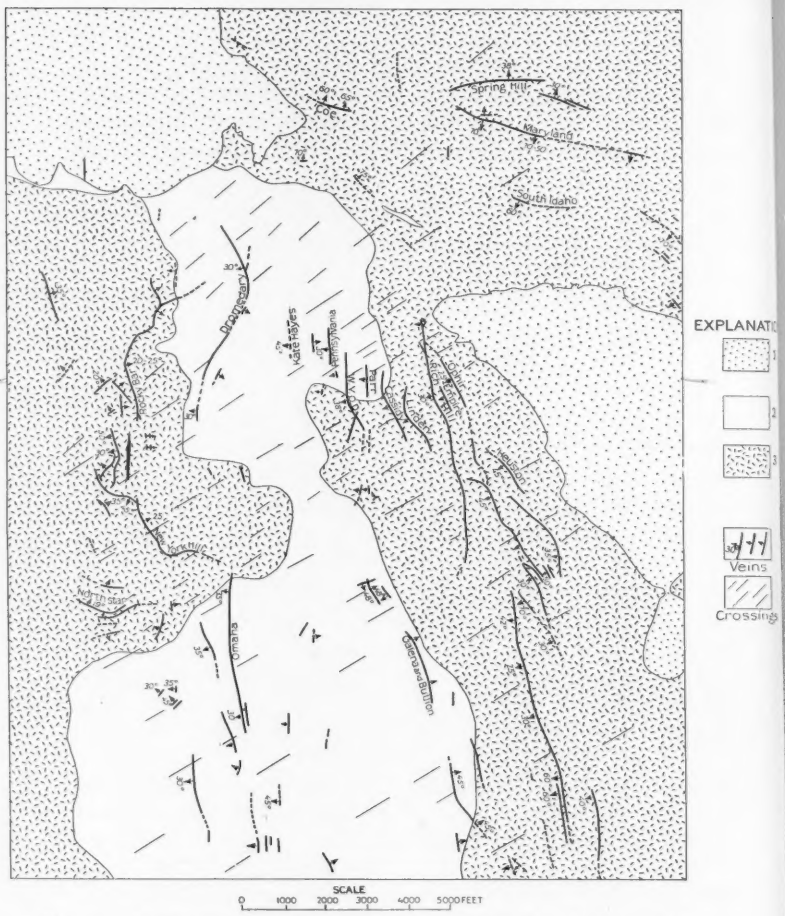

FIG. 2. Outline map of the Grass Valley quadrangle showing vein outcrops and the strike of the crossings. After Lindgren. (1) Post-granodiorite, gravels and flows. (2) Granodiorite. (3) Pre-granodiorite rocks

FIG. 3. Isometric projection of the Grass Valley quadrangle cut parallel to the shaft of the Empire Mine. Crossings are diagrammatic. (1) Post-granodiorite, gravels and flows. (2) Granodiorite. (3) Pre-granodiorite rocks.

granodiorite are extremely scarce. The granodiorite shows almost no evidence of flow structure (linear stretching or platy foliation), although Cloos observed faint platy elements paralleling the intrusive contact at two or three places in the Empire mine.

Dikes.—Numerous dikes cut the granodiorite and extend into the adjoining rock. Mineralogically they fall into two groups—the aplites, which have a fairly uniform composition, and the basic dikes, which have a wide range in composition. The dikes of both groups have sharp and regular walls which show no evi-

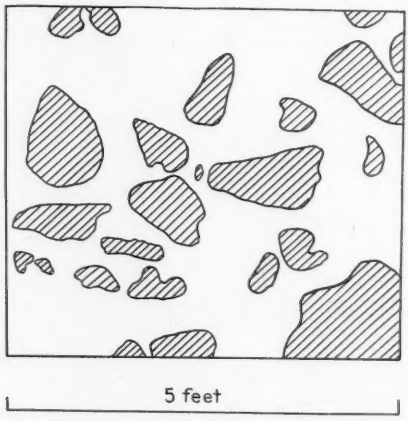

FIG. 4. Autoliths (segregations) in the granodiorite showing characteristic lack of orientation. Empire shaft below 1700 level. Traced from a photograph.

dence of assimilation of the host rock, and some of the aplites show definitely chilled borders. The majority of the dikes, like the crossings, strike northeasterly.

The Vein Fractures.—The principal outcropping veins are shown in Fig. 2. Howe[6] called attention to the preponderance of veins that strike north parallel to the long axis and walls of the intrusion. The W. Y. O. D.-Pennsylvania group of veins (Fig. 2) strike across the local contact but, as shown in Fig.

[6] Howe, Ernest: *Op. cit.*, p. 603.

3, the contact intersected is that of a roof pendant of the older rocks, and these veins, too, may be considered parallel to the main contact. This relation also holds true for most of the veins of easterly strike, notably those in the North Star and New York Hill groups, which also strike parallel to the granodiorite contact at the horizon at which they enter the intrusive.

The principal true exceptions to this parallelism are the Idaho-Maryland and Brunswick group of veins, which are remote from the known granodiorite contact, and the Wisconsin and Omaha group of veins, which cross the contact with the host rock at a high angle. Mining development, however, has shown that although the Omaha veins cross the contact with the intruded rock, they cannot be traced far in it. Similarly, the veins of the northward-striking Empire system within the granodiorite do not extend beyond the northern end of the intrusive, but near the contact they are dissipated in a network of small veins with random strikes.

As pointed out by Lindgren,[7] "each direction of strike has its two directions of symmetrically opposite dip, which are referred to as *conjugated systems.*" Thus, in a pair of veins paralleling some part of the granodiorite host-rock contact, one vein dips into the intrusive and the other dips into the host rock. In this connection it may be noted that the veins dipping into the intrusive are generally the more persistent.

The vein fractures are not simple breaks but rather are fracture *zones* of variable width and degree of shattering, within which the veins as defined by the quartz filling are confined. Secondary walls diverge from both the hanging and foot walls of the main vein at low angles, forming "feather joint systems." In many places a marked increase in the number of diverging secondary walls furnishes a clue for picking up a parallel quartz vein within the principal outer walls of the same vein zone.

It was possible to determine the displacement on the veins in only a few places where the offset of dikes could be measured. In all such places the displacement was reverse with a maximum measured movement of approximately 20 feet. In many places

[7] Lindgren, Waldemar: *Op. cit.*, p. 259.

brecciation of the vein filling and gouge seams in the quartz are indications of post-mineral deformation.

The Crossings.—The crossings are vertical or steeply dipping joints. In places they are simple fractures and elsewhere they form sheeted fracture zones several feet in width. Some of the fractures are tightly closed; others are open and form water-courses through which surface water descends into the mine workings. Some have gouge; others have none. In contrast to the veins, few crossings contain quartz, although there are exceptions to this rule. Detailed underground mapping shows that most individual crossings are rather short, but locally some form zones which are relatively persistent. Although there is little displacement along either vein or crossing walls where they intersect, offsets of both kinds do occur.

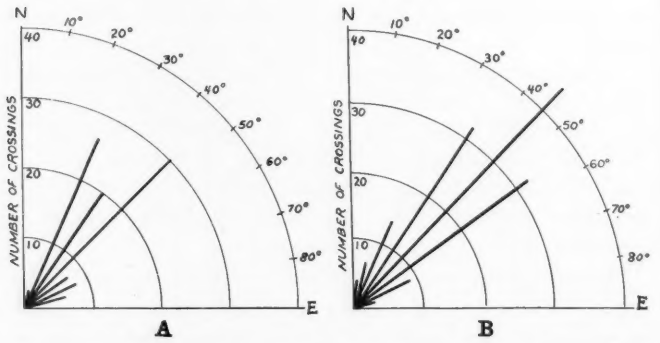

FIG. 5. Strike of crossings. Length of line indicates the number of crossings striking in each 10° arc. (*A*) Empire Mine, 4200 to 7000 levels inclusive; 101 crossings plotted. (*B*) North Star Mine, drifts on No. 2 vein; 144 crossings plotted.

As shown in the accompanying diagrams of strike frequency (Fig. 5), all the crossings strike northeasterly, approximately transverse to the long axis of the intrusion. This fact immediately suggests two possible explanations for their origin: that, (*a*) as advanced by Howe, they may be tension cracks developed

in an arched dome, or (*b*) they may be shrinkage cracks developed during the cooling of the granodiorite. There is, however, a third possible explanation—namely, that the crossings belong to a regional joint system developed independently of the intrusion. Recent work by Cloos in the middle Sierra Nevada has shown the existence of a northeastward-striking joint system of wide extent which he has mapped from Donner Pass to the Yosemite, over an area of 7500 square miles. Joints of this system cut

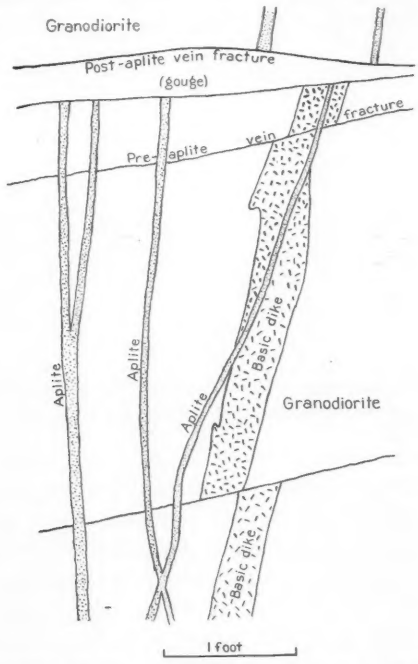

FIG. 6. Sketch of a vein footwall on 7200 level, North Star Mine, showing the following sequence:

(1) Opening of NE-striking fracture (crossing) and injection of basic dike; (2) Pre-aplite offset along vein fractures; (3) Opening of new NE-striking fractures (crossings) and injection of aplite dikes; (4) Post-aplite offset along vein fractures.

across all geological boundaries, including intrusive contacts. They also cut across, and hence are later than, the primary joints within the major intrusive masses of the Sierra Nevada. These regional relations have led the authors to believe that the approximate coincidence of the strike of the crossings with the short axis of the Grass Valley intrusive is fortuitous.

An additional observation is that the horizontal components of the striations on the walls of the vein fractures also strike northeast parallel to the strike of the crossings. This holds true irrespective of changes in strike of the vein.

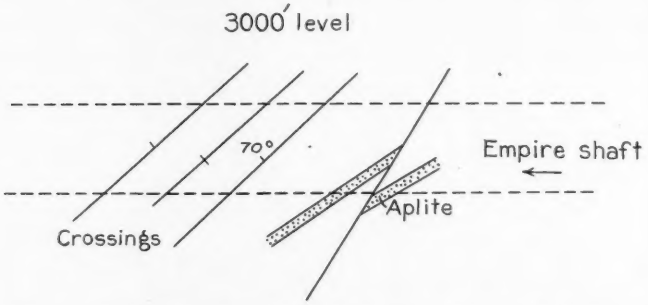

FIG. 7. Horizontal projection of fractures in Empire shaft at 3000 level, showing aplite dike offset by a crossing fracture. Arrow indicates slope of the shaft.

Evidence for the Sequence of Crossings, Dikes, and Veins.—Criteria for determining the age relationships of the different structural elements are: (1) the displacement on veins and crossings, (2) their relations at intersections, and (3) their distribution. Although evidence of cross-cutting relationships is not as abundant as might be desired, a number of definite underground exposures have been found. In the accompanying sketches (Figs. 6 to 12) the sequence, as established by each exposure, is described in the legend:

The following general sequence has been established:

(1) Primary vein fractures were formed at the closing stage of magma consolidation. These fractures extend into the in-

vaded rock up or down the dip, but they do not extend into the older rock along the strike. They are restricted to the intrusive and its surroundings.

(2) Joints (crossings) with northeast strikes and steep dips were formed, many later occupied by basic dikes. These joints (crossings) and dikes cut across primary vein fractures.

(3) Basic dikes were offset along vein fractures, indicating post-crossing movements along the vein fractures.

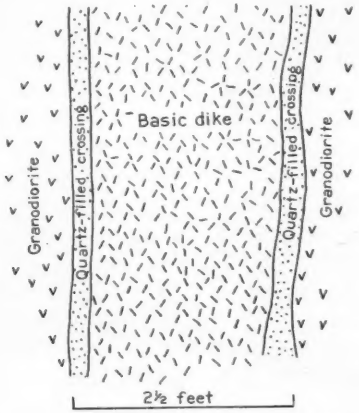

FIG. 8. Sketch of drift wall on 4600 level, Empire Mine, showing the following sequence: (1) Opening of NE-striking fracture (crossing) and injection of basic dike; (2) Reopening of crossings along the dike-walls and filling by quartz.

(4) Aplitic dikes were intruded along crossing fractures and cut across basic dikes.

(5) Aplites were offset on (*a*) vein fractures, and (*b*) crossings.

(6) Vein fractures were filled with quartz.

(7) Post-quartz thrust movements took place along the veins and offset all earlier features. Several generations of quartz indicate repeated movements.

(8) Renewed formation of crossings which offset the veins.

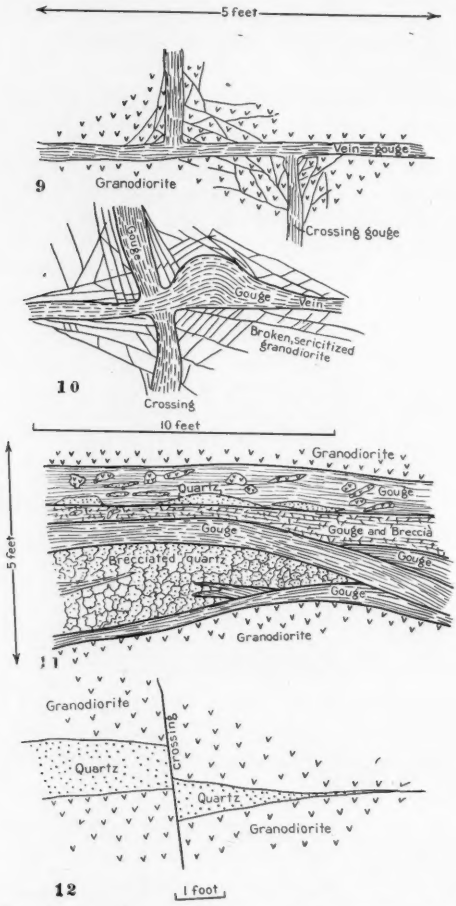

FIG. 9. Sketch of drift-wall on 5600 level, North Star Mine, showing crossing offset along vein-fracture.

FIG. 10. Sketch of drift-wall on 5600 level, North Star Mine, showing post-crossing movement on vein-fracture without horizontal displacement of the crossing.

FIG. 11. Sketch of No. 1 vein, 6600 level, North Star Mine, showing brecciated quartz cut by later gouge. Distinct gouge zones indicate at least four periods of movement.

FIG. 12. Sketch of No. 2 vein, 7200 level, North Star Mine, showing vein offset along crossing.

THE SYNTHESIS.

Previous Views.—Lindgren [8] suggested that the fissure systems are of regional origin—" produced by a succession of compressive stresses applied in different directions, chiefly from east to west and from north to south."

Howe [9] regarded the fissure systems as structural elements of the intrusion itself. The crossings he believed to be closed, primary tension joints, and he regarded the vein fractures as thrust planes relieving the inward pressure of the host rocks when deep-seated withdrawal of granodiorite magma took place. This deep-seated withdrawal resulted, he believed, in the sagging of the solidified domed roof of intrusion and the closing of the tension cracks or crossings.

The writers are in accord with Howe in regarding the vein systems as structural developments of the intrusion itself. They find difficulty, however, in admitting the need for a deep-seated withdrawal of magma to account for the marginal position of the vein fractures, not only in the Grass Valley area, but also in similar intrusive masses of wide geographic distribution. The writers' study of the Grass Valley district in the light of extended observations within the Sierra Nevada leads them to regard the crossings as of regional origin. With these differences of interpretation in mind, a modified structural history of the fracture systems is here presented.

The Plastic Stage.—The granodiorite exposed at the surface in the Grass Valley area lies near the top of the intrusive body. This conclusion is indicated by the roof pendants, such as that cut by the W. Y. O. D. shaft, that are exposed in underground workings, by the rapid downward widening of the granodiorite body, and, as might be expected in a cupola where little differential movement of magma takes place, by the relative scarcity of primary platy or linear flow structure.

The sharp character of the contact of the granodiorite with the invaded rocks and the absence of swarms of xenoliths near

[8] Lindgren, Waldemar: *Op. cit.*, p. 170.

[9] Howe, Ernest: *Op. cit.*, pp. 602–603.

the contact lead the writers to suggest that the intrusion grew by the slow pushing apart of the wall rocks.

Evidence of primary flow in the granodiorite is scarce. Schlieren are rare, and inclusions (autoliths and xenoliths) show little or no orientation. Thus, the early history of the intrusive must be interpreted largely from negative characteristics rather than from a study of the primary textures and structures, such as are found elsewhere. In contrast, both platy and linear flow structures occur on the margins of the Nevada City granodiorite, which is believed to be eroded to a deeper horizon than is the Grass Valley mass. These structural elements are well shown in the granodiorite exposures along the Calaveras-granodiorite contact in Deer Creek, near the Champion mine.

Another line of approach to the problem lies in the application of the numerous observations on the "internal tectonics"—*e.g.*, joint and dike systems—of intrusives which have been made by H. Cloos and his associates.

The Grass Valley picture, so synthesized, is of the relatively small cupola of a greater intrusive mass where, as the static magma cooled, it passed from a state of viscosity to one of rigidity without great internal differential movement.

The Rigid Stage.—As long as the magma was fluid, pressure transmitted from below would be uniformly exerted on the walls and roof of the containing chamber. With the onset of freezing, however, such hydrostatic adjustment was no longer possible, and during the stage of incipient rigidity, the continuing upward impulse of the intruding magma resulted in the opening of thrust fractures dipping into the intrusive. The first fractures that developed in larger igneous bodies—*e.g.*, on the eastern and western margins of the Sierra Nevada intrusive in the Yosemite region—are of this type. Since the solidified magma has a rigidity comparable with that of the older rocks, the fractures developed in the granodiorite continue outward into the host rock. These adjustments of upward impulse from the magma, which began in the stage of incipient rigidity, continued into the rigid stage.

The similarity of these vein fractures to the marginal thrusts of the Yosemite region has already been noted. They are believed to be primary fractures in the strictest sense—fractures developed as a result of stresses imposed by the intrusive itself, although afterward they served for the adjustment of regional stresses. That they were not open in the early stage is inferred from the absence of marginal dikes with low dips.

Following upon the incipient development of the vein fractures and before the last of the basic dike magma was exhausted, the earliest crossings were opened in response to regional stresses. The same regional stresses were responsible for later movements on the vein fracture system which accompanied or alternated with the opening of new crossings.

There is no recognizable record from which the interval elapsing between the injection of the last of the aplites and the beginning of vein-filling may be inferred. It is certain, however, that movement along the vein fractures continued during the process of vein-filling, and the abundance of gouge zones cutting the quartz is witness to the fact that movement continued after vein-filling had ceased.

SUMMARY.

In the foregoing outline of the structural history of the Grass Valley intrusive the vein fractures are regarded as elements of the internal tectonics of the intrusive body itself. They originated in an early stage of the structural development of the region, and are equivalent to the marginal thrusts observed in the Yosemite and along the Mother Lode system. As such, the vein fractures are of local origin, since they are entirely restricted to the neighborhood of intrusive contacts. As the area of consolidation within the Sierra Nevada batholith increased, larger units were affected by tectonic stresses, and joints were formed which belong to a system of regional extent. As this system has been observed over an area of at least 7500 square miles, its regional character seems proven. Basic dikes and aplites follow the cross-

ing system, and thus indicate that the earliest crossings were formed when magma to fill them was still available.

Both fissure systems repeatedly served for adjustment of later stresses, as can be proved by relative mutual displacements and by the repeated fracturing and renewed deposition of quartz within the vein fissures. It is probable that these later stresses were regional in character.

U. S. Geological Survey,
Washington, D. C.

Johns Hopkins University,
Baltimore, Md.

PARAGENESIS OF THE OXIDIZED ORES OF COPPER.

G. M. SCHWARTZ.

INTRODUCTION.

ALTHOUGH the sulphide ores of copper have been intensively studied by microscopic methods since the first application of vertical illumination to the study of ores, the oxidized ores seem to have been somewhat neglected during the same interval. Whereas some details of foreign occurrences are available in Doelter's "Handbuch der Mineralchemie," there is little available for American ores, and this is in detailed reports of districts published by the United States Geological Survey. This lack of detailed microscopic study of the oxidized copper ores is probably a result of several causes. Normally the oxidized zone is relatively superficial, and unless collections are made at the proper time good suites are not available. The commercial interest is, of course, not as great as in the sulphide ores. Furthermore, the study of the oxidized ores is rendered difficult by the fact that the minerals are partly opaque and partly transparent, and as a rule porous and vuggy. The proper study can be carried out only by combining the examination of polished surfaces, of thin sections, and of hand specimens, by determining the index of doubtful minerals by the use of the oil immersion method, and by partial analysis.

It has perhaps been generally believed that the oxidized minerals lack the regularity of occurrence of the sulphide minerals. That this is only partly true is shown by the present study. The writer first observed a fairly definite paragenetic order in some of the polished oxidized ores from the Globe district.[1] Since that time every opportunity has been taken to collect specimens which might add to the knowledge of the paragenesis of the oxi-

[1] Schwartz, G. M.: Notes on the Textures and Relationships in the Globe Copper Ores. ECON. GEOL., vol. 16, pp. 322–329, 1921.

dized copper ores. This paper is based on a detailed microscopic study of nearly 150 specimens from many widely scattered districts.

The work of previous investigators is referred to briefly in the discussion of each mineral.

Acknowledgments.—The work on which this paper is based was aided by a grant from the research funds of the Graduate School of the University of Minnesota. Partial chemical analyses were made by Dr. R. B. Ellestad. The writer is indebted to Dr. F. F. Grout for checking some of the microscopic studies. Mr. M. M. Stephens assisted in much of the work, and Dr. J. W. Gruner kindly read the manuscript.

Methods of Study.—Suitable pieces of each specimen were polished and one or more chips were selected for thin sections, if necessary. The microscopic study was made by using all methods on a given specimen before going on to the next. The polished surface was studied by vertical illumination and by a Silverman illuminator. Thin sections were studied by plain and polarized light and with the Silverman illuminator. The polished and unpolished fragments were then examined with a binocular microscope. When necessary, powdered fragments were immersed in oil to determine the index accurately as a check on identification. The writer found the Silverman illuminator particularly useful in studying these ores, especially on polished surfaces, where the true color is frequently masked by vertical illumination. It is most convenient to arrange the set-up so that the type of illumination can be varied by turning the switch without disturbing the specimen.

COPPER MINERALS OF THE OXIDE ZONE.

The copper minerals that normally form and exist in the oxide zone are numerous. The most up-to-date list is that given in the Fourth Edition of Dana's Textbook of Mineralogy, where 94 of the copper minerals are those which would be expected to occur only or mainly in the oxide zone. The list includes at least one representative of each chemical group of minerals that form in this zone; namely: chlorides, iodides, sulphates, phosphates,

arsenates, antimonates, vanadates, nitrates, carbonates, silicates, selanates, chromates, and oxides. Sulphates and arsenates are most abundant, with 24 specimens each; chlorides with 10, and phosphates with 9, rank next, and some other groups have several members.

Fortunately out of this maze of mineral species there are only a few which are found in most deposits. The minerals that are universal enough to warrant detailed study are the following:

Native copper	Cu
Cuprite	Cu_2O
Tenorite (Melaconite)	CuO
Malachite	$Cu_2(OH)_2CO_3$ or $CuCO_3.Cu(OH)_2$
Azurite	$Cu_3(OH)_2(CO_3)_2$ or $2CuCO_3.Cu(OH)_2$
Chrysocolla group	$CuSiO_3.2H_2O$ (etc.)
Copper pitch	Indefinite mixture of various earthy materials

Many associated minerals are important, notably the copper sulphides from which the oxidized minerals were derived and the common minerals of the oxide zone, particularly the iron oxides.

Description of Important Minerals.

Cuprite. Cuprous oxide forms one of the most characteristic and important minerals in oxidized copper ores, and its red internal color makes its identification easy as a rule. Of the 136 specimens examined microscopically in the present investigation, 46 contained easily recognizable cuprite. It seems probable that in some other specimens it is masked by darker constituents.

Judging from the available specimens, cuprite normally forms by direct oxidation of copper sulphides, especially chalcocite (Fig. 1). This opinion seems to be verified by many of the descriptions of copper deposits. It commonly occurs just above the chalcocite zone. In a majority of specimens the cuprite is in turn partially altered to malachite, commonly with a narrow zone of black material between the oxide and carbonate. Much of the cuprite is cut by a network of veinlets containing malachite, and masses of cuprite are coated with the same mineral. Less often other associations of cuprite occur. Ores from Bisbee, Arizona, show remnants of cuprite in a limonite boxwork (Fig 2), and

the capillary or acicular form of cuprite known as chalcotrichite associated with native copper. Ore from Globe, Arizona, shows a partial replacement of cuprite by chrysocolla.

The common massive cuprite is mostly rather coarsely granular, as may be easily observed on polished surfaces. Spencer [2] attributes this massive type at Ely, Nevada, to a direct origin from chalcocite. A rather characteristic feature of massive cuprite is the occurrence in it of disseminated specks of native copper.

In the material at hand faceted crystals of cuprite were comparatively uncommon. Small octahedrons altered on the outside to malachite were observed lining vugs in an ore from Bisbee, and another contained the chalcotrichite crystals mentioned above. A review of the literature [3] indicates that good crystals are common, but it is probably safe to say that they are not abundant.

Malachite.—Malachite is by far the most abundant copper mineral in the oxidized zone of copper deposits. It was recognized in 122 out of the 136 specimens utilized. It replaces both sulphides and oxides on a large scale, but is in turn replaced by other minerals only to a minor extent. It is most abundant in deposits that are enclosed in limestone [4] but evidently it is easily formed by carbonated waters that obtain their carbon dioxide from the atmosphere.

In the ores observed malachite was commonly formed in one of three ways:

1. By direct replacement of copper sulphides, especially chalcocite.

[2] Spencer, A. C.: The Geology and Ore Deposits of Ely, Nevada. U. S. Geol. Survey, Prof. Paper 96, p. 101, 1917.

[3] See, for example: Rogers, A. F.: Minerals Observed on Buried Chinese Coins of the Seventeenth Century. Amer. Geol., vol. 31, pp. 43–46, 1903. Lindgren, W.: The Copper Deposits of the Clifton-Morenci District, Arizona. U. S. Geol. Survey, Prof. Paper 43, p. 106, 1905. Butler, B. S.: Geology and Ore Deposits of the San Francisco and Adjacent Districts, Utah. U. S. Geol. Survey, Prof. Paper 80, p. 97, 1913. Ransome, F. L.: The Copper Deposits of Ray and Miami, Arizona. U. S. Geol. Survey, Prof. Paper 115, p. 132, 1919.

[4] Lindgren, W.: *Op. cit.*, p. 114. Emmons, W. H.: The Enrichment of ore Deposits. U. S. Geol. Survey, Bull. 625, p. 179, 1917.

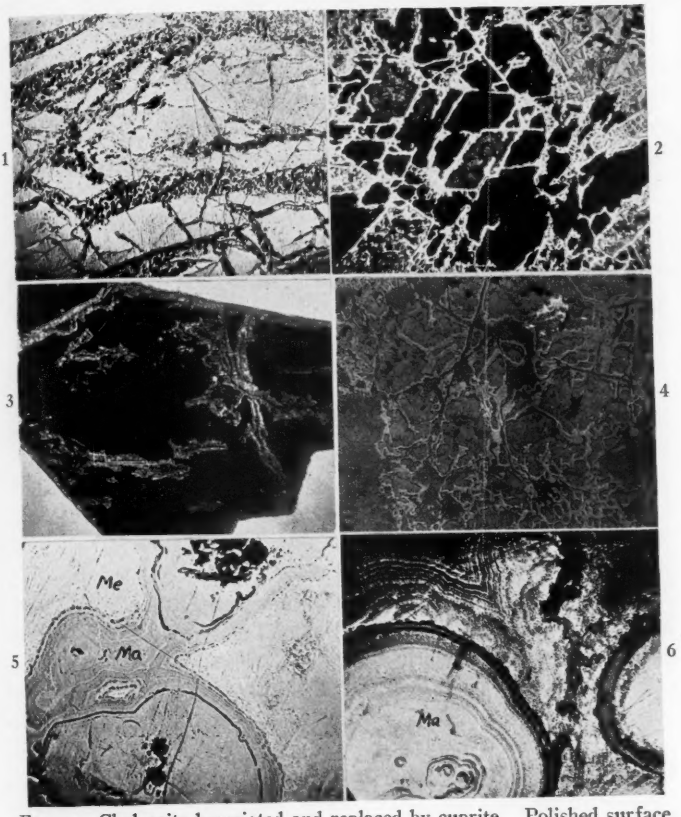

FIG. 1. Chalcocite brecciated and replaced by cuprite. Polished surface. Campbell mine, Bisbee, Ariz. × 60.

FIG. 2. Boxwork of limonite with remnants of cuprite (*c*). Polished surface. Bisbee, Ariz. × 40.

FIG. 3. Chalcocite (black) replaced by malachite around the edges and along veinlets. Thin section. Bisbee, Ariz. × 20.

FIG. 4. Enargite replaced by chalcocite (white) and malachite (dark). The chalcocite is doubtless supergene. Polished surface. Philipsburg, Mont. × 50.

FIG. 5. Melaconite (*Me*) replaced by malachite (*Ma*). Note structure in melaconite. Polished surface. Bisbee, Ariz. × 40.

FIG. 6. Malachite (*Ma*) with black oxide in typical concentric structure. Thin section. Clifton, Ariz. × 14.

2. By replacement of cuprite, usually with a thin black transition zone.

3. By precipitation from solutions in fractures, lining vugs, and on other free surfaces.

1. The direct replacement of copper sulphides is shown by chalcocite, which is commonly replaced by veinlets of malachite. The chalcocite may be massive hypogene material or a narrow rim of supergene material replacing bornite, chalcopyrite, tetrahedrite, or enargite (Figs. 3 and 4). Much supergene covellite is partially altered to malachite. Locally malachite directly replaces bornite, enargite, and tetrahedrite. In ores where chalcopyrite is the primary mineral, limonite commonly intervenes between it and malachite.

Malachite has often been described as replacing various copper minerals. Boutwell [5] mentions that it coats gray copper at Park City, Utah. Lindgren and Loughlin [6] state that both malachite and azurite form from enargite, tetrahedrite and famatinite, but they are mostly later products of oxidation resulting from the decomposition of arsenates, or result from the action of calcium carbonate solutions on soluble copper sulphate.

2. The formation of malachite from cuprite is fully as common as the direct replacement of sulphides. Commonly cuprite is cut by a network of malachite veinlets. Most of the red cuprous oxide partly changed to the green basic carbonate has a narrow transition zone of black mineral, usually referred to as copper pitch. Malachite that replaces cuprite usually develops a banded structure parallel to the contact. Where a zone of black oxide intervenes this also is banded (Fig. 5). One specimen from Globe shows cuprite forming from malachite, the reverse of the usual sequence.

3. Malachite forms freely by deposition in fractures, vugs and other openings in rock. Here there is freedom to assume its own form, and a great variety of botryoidal, mammillary and fibrous

[5] Boutwell, J. M.: Geology and Ore Deposits of the Park City District, Utah. U. S. Geol. Survey, Prof. Paper 77, p. 112, 1912.

[6] Lindgren, W., and Loughlin, G. F.: Geology and Ore Deposits of the Tintic District, Utah. U. S. Geol. Survey, Prof. Paper 107, p. 145, 1919.

aggregates result. Earthy malachite and crystalline plates also commonly form in fractures.

The shade of green of malachite seems to vary in some aggregates. This was particularly conspicuous in an excellent specimen from the United Verde Extension mine with mammillary structure. The intensity of color varies in zones along the length of the needles. Rarely the spherical masses with the color of malachite seem to be practically isotropic.

The concentric structures which malachite so often forms on free surfaces are not always composed of pure malachite, but may consist of alternating bands of two or more minerals. For example, a specimen from Clifton, Arizona, shows malachite with brownish black copper pitch in concentric rings (Fig. 6). Alternating bands of malachite and quartz were observed in some specimens (Fig 7). The quartz under crossed nicols shows a chalcedonic structure with the long axes of the grains radial. Malachite and chrysocolla are commonly associated, indicating a change from carbonate to silicate solutions and vice versa. Examples were observed of malachite deposited on chrysocolla and, to a lesser degree, of chrysocolla on malachite (Fig. 8). Obviously there is no rule here, but external conditions determine whether silicate or carbonate forms by supplying an abundance of the necessary acid radicle. That actual replacement of the carbonate may occur, is shown by ores from the Silver King mine, Park City, Utah, where veinlets of chrysocolla clearly replace malachite which had replaced sulphide.

Malachite is commonly composed of aggregates of needles. They form compact radiating groups or simply tufts of needles on free surfaces. Where calcite and malachite are in contact needles of malachite may be enclosed in the calcite so that there appears to be a gradation in color between the two. Excellent examples of this were observed in ores from Bisbee. Probably the calcite referred to by Ransome[7] as delicately banded and tinted with salts of copper was of this type.

[7] Ransome, F. L.: The Geology and Ore Deposits of the Bisbee Quadrangle. U. S. Geol. Survey, Prof. Paper 21, p. 125, 1904.

Certain rarer occurrences of malachite were also observed. In one specimen the principal mass is cuprite with only a narrow zone of malachite between it and calcite, suggesting the incidental formation of copper carbonate during the deposition of calcite on cuprite.

Malachite occurs also as needles in quartz. Rarely malachite is coarsely crystalline. In a specimen from Nemo, South Dakota, the malachite crystals resembled the common forms displayed by calcite when deposited in openings.

Azurite.—The beautiful blue color of azurite makes it a conspicuous constituent of oxidized copper ores, but it is much less abundant than malachite, as is indicated by the fact that it was found in but 41 out of 136 specimens examined. This has been noted previously by Butler,[8] Emmons,[9] and others.

Azurite occurs most commonly as granular aggregates (Fig. 9) and well formed crystals deposited on free surfaces. More rarely it forms radiating aggregates such as are typical of malachite, as was well shown in an ore from Bisbee.

Azurite is almost universally associated with malachite. The two not infrequently form at the same time or alternately, but it is common to find azurite deposited on malachite. This is true at Bingham, according to Boutwell,[10] and at Globe as described by Ransome.[11] Rogers [12] found azurite later than malachite on buried coins. Lindgren [13] notes that at Morenci azurite occurs as crusts alternating with malachite and often with kaolin and copper pitch, but commonly it is the latest mineral.

Azurite commonly replaces cuprite as veinlets and in one specimen surrounds spherical aggregates of cuprite. Concentric or radiating aggregates of azurite are embedded in clay from the Daly West mine at Park City, Utah. Crystals of azurite in ore

[8] Butler, B. S.: *Op. cit.*, p. 97.

[9] Emmons, W. H.: *Op. cit.*, p. 179.

[10] Boutwell, J. M.: Economic Geology of the Bingham Mining District. U. S. Geol. Survey, Prof. Paper 38, p. 109, 1905.

[11] Ransome, F. L.: Geology of the Globe Mining District, Arizona. U. S. Geol. Survey, Prof. Paper 12, p. 123, 1903.

[12] *Op. cit.*

[13] Lindgren, W.: *Op. cit.*, p. 114.

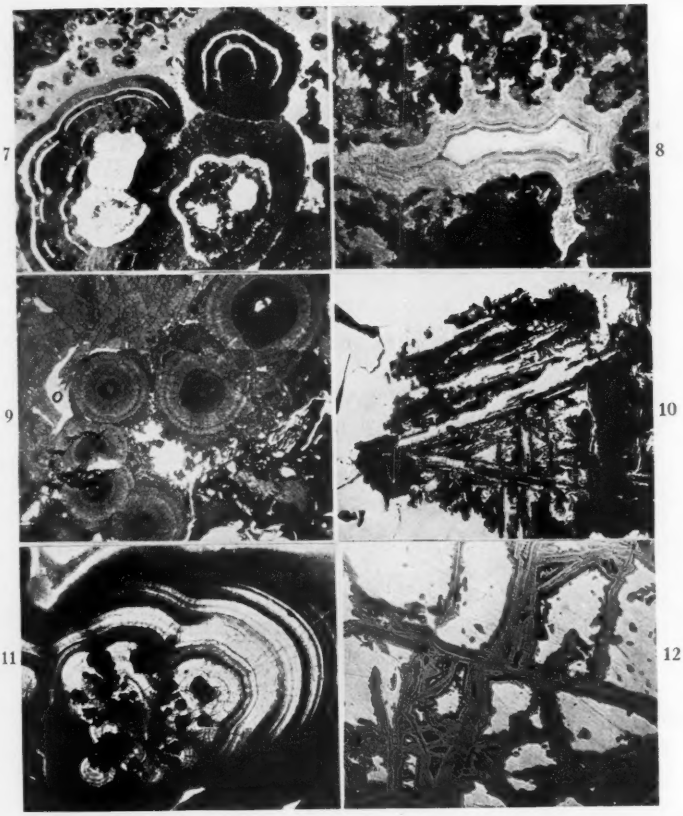

FIG. 7. Concentric structure of malachite (dark) and quartz (light). Thin section. Locality unknown. × 15.

FIG. 8. Chrysocolla lining vug in malachite. Thin section. × 28.

FIG. 9. Concentric structures of malachite with azurite and quartz (*O*). Thin section. Ajo pit, Ariz. × 14.

FIG. 10. Native copper replacing chalcocite. Mufulira mine, N. Rhodesia. × 60.

FIG. 11. Black oxide (melaconite?) rosettes in malachite. Thin section. Globe, Ariz. × 20.

FIG. 12. Veinlets of limonite replacing chalcopyrite. Polished surface. Calumet and Arizona mine, Bisbee, Ariz. × 80.

from the Manganese Blue mine, Morenci, Arizona, were partly altered to malachite, a reversal of the usual sequence.

Azurite does not appear to replace sulphides directly as a rule, but a specimen from the Black Hills of South Dakota shows veinlets of azurite in chalcopyrite with limonite intervening, and an ore from Indian Springs, Nevada, shows azurite in veinlets cutting chalcocite and bornite. Emmons and Calkins [14] describe azurite formed by oxidation of tetrahedrite at Philipsburg, Montana, and Boutwell [15] mentions azurite coating tetrahedrite, which it may have partly replaced.

Malachite and azurite commonly occur as crystals and aggregates lining vugs and other free surfaces, where they have been deposited from solutions. In some examples the copper has doubtless traveled some distance; in others it is deposited in openings within the ore from which it was dissolved.

Native Copper.—The following notes apply only to native copper of the oxidized zone. Its occurrence in hypogene deposits has been carefully studied during the recent work [16] on the Michigan deposits, and need not be summarized here. Although native copper is usually reported in the oxidized zone of copper deposits, the present study revealed it in only about twelve per cent. of the specimens examined and mostly in small amounts. Its general occurrence in such ores is summarized by W. H. Emmons.[17]

Native copper in the oxidized ores occurs most commonly as small grains in cuprite where it probably formed during the oxidation of chalcocite to cuprite. It also occurs as crystals deposited on the walls of vugs in limonitic specimens. This type of occurrence has also been noted by Rogers.[18] It is characteristic enough to suggest that the iron oxide acts as a precipitant.

[14] Emmons, W. H., and Calkins, F. C.: Geology and Ore Deposits of the Philipsburg Quadrangle, Montana. U. S. Geol. Survey, Prof. Paper 78, p. 157, 1913.

[15] Boutwell, J. M.: Geology and Ore Deposits of the Park City District, Utah. U. S. Geol. Survey, Prof. Paper 77, p. 112, 1912.

[16] Butler, B. S., and others: The Copper Deposits of Michigan. U. S. Geol. Survey, Prof. Paper 144, 1929. Wells, R. C.: Chemistry and Deposition of Native Copper from Ascending Solutions. U. S. Geol. Survey, Bull. 778, 1925.

[17] Emmons, W. H.: *Op. cit.*, p. 176.

[18] Rogers, A. F.: Notes on Some Pseudomorphs, Petrifactions and Alterations. Amer. Phil. Soc. Proc., vol. 49, p. 17, 1910.

Native copper also replaces chalcocite, as was described by Graton and Murdock [19] in ores from the Old Dominion mine, Globe, Arizona, and as has been inferred by several writers. It was observed by the writer in ore from Globe and especially in specimens from the Mufulira mine, Northern Rhodesia, which were supplied by Dr. D. M. Davidson. In these specimens native copper occurs as rims around areas of chalcocite and penetrating it along fractures and possibly cleavage (Fig. 10). The field relations indicate, according to Dr. Davidson,[20] that the native copper is a result of supergene processes.

Lindgren [21] states that native copper is commonly found with cuprite at the upper limit of the chalcocite zone at Morenci, Arizona, where it is intergrown with cuprite and is covered with carbonates, silicates and sulphates of copper. In general, native copper does not seem to form in chalcocite as commonly as it does in cuprite, which often has been derived from chalcocite, but nevertheless the formation direct from cuprous sulphide is common enough to be of significance as a process in the oxidation of copper ores.

Although native copper often forms from cuprite, the reverse also happens and native copper oxidizes to cuprite, as was especially well illustrated in a specimen from Ajo, Arizona, supplied by Mr. W. C. Lawson. This consists of a nodular, somewhat porous mass about two inches in diameter, with a core containing numerous residual areas of native copper surrounded by cuprite. The vugs and outside are covered with malachite. The same sequence was noted in ores from the Campbell mine, Bisbee, Arizona.

Chrysocolla.—The most perplexing questions regarding the paragenesis of the oxidized copper ores were raised by the material usually referred to as chrysocolla, but which is in reality a group of minerals rather than a single species. Lindgren [22] de-

[19] Graton, L. C., and Murdock, Joseph: The Sulphide Ores of Copper. Trans. Amer. Inst. Min. Eng., vol. 45, p. 56, 1914.

[20] Personal communication.

[21] Lindgren, W.: *Op. cit.*, p. 101.

[22] Lindgren, W.: *Op. cit.*, p. 112.

scribed the characteristics of some of the varieties in his report on the Clifton-Morenci deposits. More detailed work has been done by Schaller,[23] who believes the group contains eight species, but completion of his study depends on securing suitable material for analysis.[24] The writer suggests that geologists assist in working out the details of this group by sending available specimens which seem suitable for analysis to Dr. Schaller at the United States Geological Survey. The chief difficulties arise from the fact that the varieties seldom occur alone but rather as extremely intricate mixtures of two or more varieties of chrysocolla, with chalcedony and malachite commonly associated.

The following varieties seem to be common:

(1) Closely resembling opal with light green color, conchoidal fracture, ranging from isotropic to slightly anisotropic. Index of refraction close to 1.46.

(2) With highly developed spherulitic structure. Color bluish opalescent. Index of refraction about 1.504 and high birefringence. The extinction is parallel, giving well developed crosses due to extinction in the spherulites.

(3) Resembles the first kind in hand specimens, but has an index about 1.53, with high birefringence.

The manner in which the varieties are associated is brought out by the following notes.

Material from Hillside, Arizona, with the blue-green color of common chrysocolla, shows under the microscope a uniform green color; but under crossed nicols proves to be a complex mixture of amorphous and highly birefringent minerals with spherulitic structures. Quartz and chalcedony are associated.

A specimen from Ray, Arizona, is composed mainly of spherulitic aggregates of highly birefringent chrysocolla with colloform structure in plain light. This material seems remarkably uniform in plain light, but under crossed nicols it appears very complex, with veinlets of a later generation cutting the earlier

[23] Ransome, F. L., The Copper Deposits of Ray and Morenci, Arizona. U. S. Geol. Survey, Prof. Paper 115, p. 140, 1919. Schaller, W. T.: Abstract. Amer. Min., vol. 16, p. 112, 1931.

[24] Personal communication from W. T. Schaller.

chrysocolla and some apparently amorphous layers in the spherulites.

There is frequently such a close association of chrysocolla and chalcedony that it is hard to distinguish them. A thin section of an ore from Bisbee shows this clearly. In plain light much of the material is light green to colorless, but the whole shows colloidal structure. Under crossed nicols there is a confused mass ranging from isotropic to cryptocrystalline-fibrous, with a highly birefringent mineral filling a network of cracks. At least part of the chalcedonic material (some now recrystallized to quartz) fills what were vugs in the chrysocolla of the highly birefringent variety.

The amorphous variety of chrysocolla is well shown in a specimen from a collection by C. W. Hall, locality unknown. Some of this material has a blue-green color in thin section and appears uniform in plain light. Under polarized light, portions are apparently completely isotropic, but these are crossed by veinlets of a pleochroic and highly birefringent species. Other portions of the slide show colors varying from almost colorless and light green to bright blue. This color variation suggests variation in composition within a species.

A specimen from Jerome, Arizona, shows the slightly birefringent mineral with chalcedonic structure cut by veinlets of a highly birefringent type.

In spite of the fact that there are several varieties, chrysocolla may be treated as a group and some generalizations may be made regarding its relation to the other copper minerals of the oxidized zone. As a rule chrysocolla seems to form relatively late in the process of oxidation, as is shown by the fact that it commonly lines vugs (Fig. 8), where it is deposited on malachite and other copper minerals. It is cut by veinlets of malachite in a few specimens. Veinlets of chrysocolla were observed cutting malachite, cuprite, limonite and black oxide. Not uncommonly chrysocolla is followed by chalcedony, indicating a decrease in the copper available for the formation of silicate. Besides filling veins, chrysocolla may replace rock minerals. A specimen from a prospect in the Boulder batholith region of Montana shows

calcite clearly replaced by chrysocolla. Rogers[25] has reported examples of this replacement. Like malachite, chrysocolla is commonly a result of transportation and redeposition of both silica and copper. It does not appear to replace sulphides directly as a rule, but it was observed replacing chalcocite from Globe, Arizona, and is reported as a product of the oxidation of tetrahedrite at Cripple Creek, Colorado.[26] Ransome[27] describes it as replacing dacite tuff at Globe, Arizona. Lindgren[28] found it more abundant in granite and porphyry than in limestone at Morenci, Arizona. A summary of the occurrence of chrysocolla will be found in the paper on enrichment by W. H Emmons.[29]

Tenorite (Melaconite) and Copper Pitch.—Tenorite as a crystalline mineral is comparatively rare. It occurs chiefly as minute black scales in volcanic regions, those from Vesuvius having been recently shown to be monoclinic.[30] The earthy or massive variety, known as melaconite, is usually described as occurring in copper veins as an oxidation product. Various similar products have been described as "copper pitch ore" and as a matter of fact there seems frequently to have been little distinction between these materials or in the use of various terms. The writer found specimens variously labeled as tenorite, melaconite and copper pitch totally unreliable. A massive porous brownish specimen from Globe which had for years been accepted as copper pitch actually contained less than one per cent. copper, but did contain 10 per cent. MnO_2 and 6.45 per cent. water, the remainder being principally silica. Other specimens on partial analysis corresponded with some of the varieties listed by Guild[31] in his recent review of "copper pitch ore."

[25] Rogers, A. F.: Notes on Some Pseudomorphs, Petrifactions and Alterations. Amer. Phil. Soc. Proc., vol. 49, p. 20, 1910.

[26] Lindgren, W., and Ransome, F. L.: Geology and Gold Deposits of the Cripple Creek District, Colorado. U. S. Geol. Survey, Prof. Paper 54, p. 129, 1906.

[27] Ransome, F. L.: Geology of the Globe Copper District. U. S. Geol. Survey, Prof. Paper, 12, p. 123, 1903.

[28] Lindgren, W.: *Op. cit.*, p. 112.

[29] Emmons, W. H.: *Op. cit.*, pp. 181–183.

[30] Tunell, G., Posnjak, E., and Ksanda, C. J.: The Crystal Structure of Tenorite (Cupric Oxide). Jour. Wash. Acad. Sci., vol. 23, pp. 195–198, 1933.

[31] Guild, F. N.: Copper Pitch Ore. Amer. Min., vol. 14, pp. 313–318, 1929.

A black or dark brownish material which might be classified under one of the above terms was recognized in over one-third of the oxidized copper ores examined. In no case was anything found that could be identified definitely as tenorite. It seems safe to conclude that definite crystalline cupric oxide is a rare constituent of oxidized copper ores. Just how abundant melaconite may be it is impossible to judge with present technique, because there is no practical manner of distinguishing it from the complex mixtures of copper, manganese, iron, silica and carbonate which make up copper pitch.

Short [32] refers to the matter under tenorite as follows:

> The massive variety, the more common, is melaconite; and the prismatic variety, tenorite. Melaconite commonly has more or less chemically combined manganese oxide and silica. If it contains more than about 5 per cent. of either of these two components, the mineral is known as "copper pitch ore."

The material which the writer found to be made up principally of cupric oxide (probably melaconite) is the narrow rim of black pitchy material that characteristically forms when cuprite (cuprous oxide) alters to malachite. Over one-fourth of the specimens in which the variable black mineral was observed are of this origin; *i.e.*, a mineral forming a zone between cuprite and malachite. A small amount of this black material was carefully selected from a specimen labeled Bisbee, Arizona, and partially analyzed by Dr. R. B. Ellestad, with the following results: Cu, 66.6 per cent.; H_2O, 6.17 per cent.; CO_2, 3.86 per cent.; Mn, none. As some malachite was inevitably included, the CO_2 may be calculated as malachite. There still remains considerable water to be accounted for, which suggests the possibility of hydrated cupric oxide being present. Thus

$$Cu_2O + O + H_2O = 2Cu(OH)_2.$$

This reasoning would indicate that the specimen is composed of 19.4 per cent. malachite, 25.4 per cent $Cu(OH)_2$, and the re-

[32] Short, M. N.: Microscopic Determination of the Ore Minerals. U. S. Geol. Survey, Bull. 825, p. 82, 1931.

mainder mainly melaconite (cupric oxide). Hydrous cupric oxide has not been recognized as a natural mineral but is known in the chemical laboratory as a synthetic compound.

Qualitative and partial quantitative analyses of several specimens containing black or dark brown oxide material indicated that the brownish material of dull luster is mostly high in manganese, whereas the black material is high in copper.

Melaconite or " copper pitch " has a varied relation to the other copper minerals. Not uncommonly the " copper pitch " occurs as bands in concentric structure with chrysocolla, malachite and azurite (Fig. 6). It seems characteristic of the brownish manganese-bearing variety to occur as concentric shells or nodules. This was conspicuously shown in specimens from the Manganese Blue mine, Morenci, Ariz. Commonly the black mineral occurs as rosettes or dendrites (Fig. 11) in malachite. It was observed as fragments in chrysocolla, and as veinlets in the same mineral; also as veinlets in malachite, although it usually precedes this mineral. A black band commonly develops when malachite, or less commonly other minerals, replace sulphides. It was also noted cut by veinlets of azurite. In other occurrences it is difficult to determine any specific relation to the various associated minerals.

It is safe to say that Dr. Guild has understated rather than overstated the complexity and variety of materials referred to as copper pitch. Apparently most specimens labeled tenorite or melaconite may be placed in the same category. The only safe method of making more specific determinations would be by qualitative and microchemical tests followed where possible by quantitative analysis. Since all are opaque and much alike in polished surface, the ordinary methods of determination are of little value.

It is of interest to note that chrysocolla on gentle heating (below redness) turns dark, the water is eliminated, and the product resembles much of the so called " copper pitch."

" Limonite."—The development of " limonite " during the oxidation and leaching of copper ores has been carefully studied

during the investigations of leached outcrops.[33] The following notes apply to those ores which have not been leached of their copper, but rather to those in which copper has frequently been deposited by the altering solutions. "Limonite"[34] was definitely recognized in 63 out of 136 specimens and it may be assumed that it was present in many others, but was masked by the highly colored copper minerals. Usually the "limonite" is present as earthy material more or less mixed with, or coating, the copper minerals. "Limonite" commonly replaces chalcopyrite as a network of veinlets (Fig. 12). At places there is a narrow zone of chalcocite between the chalcopyrite and "limonite," but more often the "limonite" replaces the chalcopyrite directly. Malachite not uncommonly fills the middle of the larger veinlets.

Iron oxide is common as pseudomorphs after pyrite crystals. This usually seems harder than most of the other occurrences and presumably is true goethite.

Much of the iron oxide found in oxidized copper ores is apparently not derived from pre-existing iron minerals *in situ*, but is evidently a result of precipitation of transported materials. For a comprehensive discussion of the factors determining the origin of "limonite" in copper ores the reader is referred to the treatise by Locke cited above.

Discussion of Paragenesis.

The data presented above show many of the complexities involved in the oxidation of copper ores. Nevertheless there is at least a semblance of an orderly series of minerals or paragenetic sequence. There are two rather well defined sequences that may be observed in the early stages of the effect of oxidizing processes on sulphide ores, whether hypogene or supergene. First, the sulphides are commonly oxidized mainly to cuprite, which is in turn oxidized to black oxide, and then hydrated and carbonated to

[33] Locke, A.: Leached Outcrops as Guides to Copper Ore. Baltimore, 1926. Blanchard, R., and Boswell, P. F.: Notes on the Oxidation Products Derived from Chalcopyrite. ECON. GEOL., vol. 20, pp. 613–638, 1925. Limonite Types derived from Bornite and Tetrahedrite. ECON. GEOL., vol. 25, pp. 557–580, 1930.

[34] The term "limonite" is used as defined by Locke, *op. cit.*, p. 167.

form malachite. As a rule the malachite does not form directly from cuprite, but a narrow rim of black oxide forms as an intermediate mineral or aggregate. Since malachite contains cupric oxide, the following reactions are indicated.

$$Cu_2O + O = 2CuO$$
$$2CuO + CO_2 + H_2O = CuCO_3.Cu(OH)_2.$$

Chalcocite, especially as a supergene mineral, commonly precedes cuprite, thus the following equation is suggested: $Cu_2S + 2O_2 + H_2O = Cu_2O + H_2SO_4$; or, following Lindgren, $2Cu_2S + O = 2CuS + Cu_2O$. A small amount of disseminated native copper is often found, having formed perhaps according to the following equation as given by W. H. Emmons:[35]

$$Cu_2O + 2FeSO_4 + H_2SO_4 = 2Cu + Fe_2(SO_4)_3 + H_2O.$$

The following seems more likely:

$$2Cu_2S + 5O = Cu_2O + 2Cu + 2SO_2.$$

Where cuprite is followed directly by malachite without the black oxide, the equation indicated is:

$$Cu_2O + H_2CO_3 + O = CuCO_3.Cu(OH)_2.$$

Rarely azurite forms directly from cuprite, probably as follows:

$$3Cu_2O + 4H_2CO_3 + 3O = 2[Cu(OH)_2.2CuCO_3] + 2H_2O.$$

The second sequence to be mentioned is the direct replacement of sulphides by malachite, presumably by the action of strongly carbonated waters which favor the formation of the basic carbonate instead of the cuprous oxide. Doelter[36] gives the following equation for the formation of malachite from chalcopyrite:

$$2CuFeS_2 + CO_2 + 6H_2O =$$
$$CuCO_3.Cu(OH)_2 + Fe_2O_3 + 4H_2S + H_2.$$

Chalcocite and covellite may alter to malachite as follows:

$$Cu_2S + CO_2 + 2H_2O + 5O = CuCO_3.Cu(OH)_2 + H_2SO_4$$
$$2CuS + CO_2 + 3H_2O + 8O = CuCO_3.Cu(OH)_2 + 2H_2SO_4.$$

[35] *Op. cit.*

[36] Doelter, C.: Handbuch der Mineralchemie, vol. 1, p. 468, 1912.

Chalcopyrite frequently alters to limonite with the solution and removal of copper, in which case the equation may be as follows:

$$CuFeS_2 + 8O = CuSO_4 + FeSO_4.$$

With bornite the reaction would probably be as follows:

$$Cu_5FeS_4 + 2H_2SO_4 + 18O = 5CuSO_4 + FeSO_4 + 2H_2O$$
$$6FeSO_4 + 3O + 3H_2O = 2Fe_2(SO_4)_3 + 2Fe(OH)_3.$$

Malachite and azurite are closely associated and seem to have no constant relation to each other. It seems most common to find azurite later than malachite, but it may be contemporaneous or later. There seems no evident chemical reason for the change from one basic carbonate to the other. It has perhaps some relation to the concentration of carbonic acid, since azurite contains a two-to-one ratio of carbonate molecule to hydroxide molecule. There is some suggestion of this in experiments made by Marx.[37] Doelter[38] gives the following equation for the change from malachite to azurite:

$$3[CuCO_3.Cu(OH)_2] + CO_2 = 2[2CuCO_3.Cu(OH)_2] + H_2O.$$

Members of the chrysocolla group form frequently at a stage in alteration close to that of malachite. This indicates the presence of considerable silica in the waters, since studies of the paragenesis of the ores rarely indicates formation of copper silicate by attack on quartz or silicate minerals. There is rather distinct evidence of its formation by colloidal silica, probably by absorption of copper.

Chalcocite rather exceptionally alters to native copper without intermediate minerals. This phenomenon was not observed in connection with other copper sulphides. W. H. Emmons[39] gives the following equations for this alteration:

$$Cu_2S + 3Fe_2(SO_4)_3 + 4H_2O = 2Cu + 6FeSO_4 + 4H_2SO_4$$
$$Cu_2S + 4Fe_2(SO_4)_3 + 4H_2O =$$
$$Cu + CuSO_4 + 8FeSO_4 + 4H_2SO_4.$$

[37] Marx, A. H.: Unpublished thesis, University of Minnesota, 1929.
[38] *Op. cit.*
[39] *Op. cit.*

For hypogene deposits Wells suggests the following reaction:[40]

$$Cu_2S + 3Fe_2O_3 + 5H_2SO_4 = 2Cu + 6FeSO_4 + 5H_2O.$$

Native copper oxidizes to cuprite and the cuprite to malachite, as noted above. The chemical reactions of this alteration are probably simple and may be written thus:

$$2Cu + O = Cu_2O \text{ (cuprite)}$$
$$Cu_2O + H_2CO_3 + O = CuCO_3.Cu(OH)_2 \text{ (malachite)}.$$

The data which have been presented in this paper show many of the relations found in oxidized copper ores They point the way to more detailed studies, especially of individual deposits or districts where the investigator may have the opportunity to collect the samples personally and record their field relations. It would be particularly desirable to have comparative studies of oxidized copper ores in different host rocks. Because of the abundance of copper carbonates in oxidized ores it seems probable that important contrasts would be found between oxidized ores in limestone and those in porphyry, granite and other host rocks. The relation of the formation of chrysocolla to the possibilities of silica in solution would also be of interest.

The work of Locke and others has emphasized the importance of the amount of pyrite which formerly existed in leached outcrops of copper ores. Perhaps there are other similar variables that affect the process of oxidation and determine the mineral species developed. Climatic conditions are unquestionably important, as shown by the local abundance of sulphates, and perhaps other variations in oxidized ores may be related to climatic factors.

SUMMARY.

1. The most common sequence in oxidized copper ores appears to be: sulphide-cuprite-melaconite (copper pitch)-malachite. Azurite takes the rôle of malachite in some occurrences, but more commonly it is associated with malachite and slightly later in time of formation.

[40] Wells, R. C.: *Op. cit.*, p. 41.

2. Much copper sulphide ore (chalcocite, covellite, bornite, chalcopyrite, tetrahedrite) alters directly to malachite; much less commonly, it alters directly to azurite. Enargite also may alter directly to malachite, but it has been shown that more often copper arsenates form and may alter later to malachite.

3. The formation of cuprite is commonly accompanied by the development of small amounts of native copper.

4. Native copper is oxidized to cuprite and the cuprite in turn carbonated and hydrated to form malachite.

5. Native copper occurs commonly with "limonite." Study of these occurrences leads to the suggestion that "limonite" may act as a precipitant for the copper.

6. Native copper forms directly from chalcocite at places but this is apparently not important quantitatively.

7. Chrysocolla usually forms late in the development of oxidized ores, but may form directly from sulphide. It is commonly closely associated with chalcedony and with malachite.

8. Chrysocolla and "copper pitch" are complex substances, as pointed out by previous investigators, and they need further study.

9. Tenorite (melaconite) as a definitely recognizable mineral in copper ores seems rare. It is probably a constituent of most "copper pitch ore."

10. Chalcopyrite is frequently replaced by a network of limonite veinlets, the copper having evidently been carried out in solution.

UNIVERSITY OF MINNESOTA,
MINNEAPOLIS, MINN.

THE MOLYBDENUM MINE AT AZEGOUR, MOROCCO.[1]

ARNOLD HEIM.

THE Azegour mine is the most recently discovered molybdenum mine, and is one of the richest known. It was discovered five years ago. The mine was formerly worked on a small scale for copper, zinc, and lead.

The first report (1),[2] containing a geological map of the district, was made in 1929, by the manager of the mine, M. F. Hébrard. A year later, a report appeared by Professor L. Duparc (2) of Geneva, who has also published several other papers (3, 4, 5). The standard work on the geology of the High Atlas of Marrakech is a volume by Professor L. Moret (7), which is accompanied by an excellent map.

Location.—The property is reached from the harbor of Casablanca by way of the former capital of Morocco, Marrakech, thence by automobile to Amismiz at the north foot of the High Atlas (a distance of 60 Km.). From this town to the mine a motor road 20 Km. long has been constructed, which rises to an elevation of about 1800 meters and then gradually descends to the mining camp, at an elevation of 1525 meters (Fig. 1).

Mining Conditions.—The concessions are owned by the Société de Recherches Minières du Falta, Paris, and the Société Le Molybdène, Geneva. Intensive mining started in 1930 and the workings now extend about half a mile from south to north. Four levels with communicating shafts had developed by the end of 1932. Zinc, lead, and copper are characteristic of the upper part of the outcrops but give way in depth to molybdenite.

The climate of Azegour is excellent. During winter and early spring, heavy snowfalls may occur but do not seriously disturb

[1] Presented before the 13th annual meeting of the Society of Economic Geologists, Princeton, N. J., July, 1933. Introduced by E. S. Moore.

[2] Numbers in parentheses refer to bibliography at the end of the paper.

the work. Excellent subsurface water is obtained from a shallow well at the lower end of the valley just above the granite.

The laborers are the efficient native Shlöhs, members of a hardy mountain tribe. Their wages for an eleven-hour day are 6 to 9 French francs.

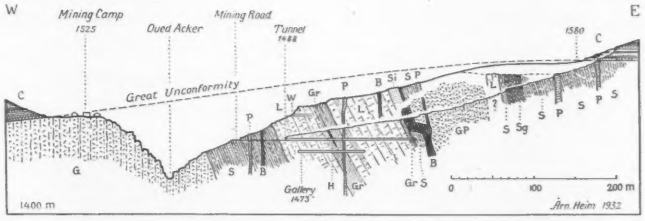

FIG. 1. Section through stope VI, molybdenum mine of Azegour. The mining camp, 400 M. farther south, is projected on the section. Note Paleozoic substructure below the great Mesozoic unconformity, composed of contact-metamorphosed Cambrian slate and limestone, intruded by the granite batholith and numerous younger dikes. *S*, spotted gray schist with andalusite, containing quartzite layers; *Sg*, same, greenish black schist; *L*, limestone and marble, partly mineralized; *Gr.*, garnetite partly impregnated with molybdenite; *W*, wollastonite rock; *H*, layer of hematite (10–25 Cm.); *Si*, siderite (11 M.); *G*, granite batholith; *GP*, granite porphyry; *P*, quartz porphyry and microgranulite; *B*, basic dikes; *C*, Lower Cretaceous (Valangian) red clay and marl with sandstone layers.

GENERAL GEOLOGY.

South of the great alluvial plain of Marrakech, the High Atlas rises at Amismiz in the form of an autochtonous fold, here referred to as the anticline of Azegour, an upright but asymmetric anticline with gently dipping south limb and steep, locally overturned north limb. At Amismiz, its axis dips east at an angle of 10–25 degrees. The nucleus of the fold is composed of Paleozoic, chiefly Cambrian, schists and limestones which are intruded by a granite batholith and numerous quartz porphyry and dark green basic dikes. The basic dikes are the younger, since some of them cut the acid rocks.

The Paleozoic rocks are unconformably overlain by non-metamorphic and gently folded Mesozoic strata. At Azegour, the base of the Mesozoic series is a red clay, including sandstone, conglomerate, and arkose layers at the base (Valangian). Above these basal beds is a great thickness of well stratified marine marls with white, yellow, green and purple marls with limestone beds, which represent the entire Cretaceous period. The Senonian series is overlain by phosphoritic marls and limestones of Eocene age (6).

Behind and above the Azegour anticline is the high range of Djebel Erdouz (3,500 M.) It is composed of more or less metamorphic Cambrian strata, involved in Hercynian folding that trends obliquely to the later Alpine folds imposed on the Mesozoic-Eocene rocks.

The contact between the Mesozoic rocks on the anticline of Azegour and the older formations of Djebel Erdouz is exposed at Medinet, where there occurs a typical example of a recumbent (east-west) fold over which is thrust (from the south) the older Hercynian basement of Djebel Erdouz—a striking example of the divergence of direction between the folds of Hercynian and Alpine structure. The Alpine movement is responsible for the formation of the anticline Azegour and for the thrust above.

Geology of the Mine.

Rocks.—The molybdenum ore is restricted to the metamorphosed Cambrian limestones in the neighborhood of the granite batholith and its offshoots. According to the investigations of Duparc there is hardly any doubt that the molybdenite is of pneumatolitic origin in connection with the intrusion of the batholith. Contact metamorphism, in addition to regional metamorphism, has affected the Cambrian strata over a width of more than 500 meters across the strike to the north, and over 1.5 kilometers along the strike from the last granitic outcrop (Tisgui-Antifa). The most important limestone (Azegour-Antifa) is intercalated with quartzite and dips 45°–75° E. Its thickness varies from 50 to more than 150 meters (Fig. 1),

averaging 80–100 meters. Apparently it is a part of the eastern limb of the anticline of Djebel Tisguine (2074 M.).

Contact metamorphism has affected all of the rocks. The most thoroughly metamorphosed types are rocks which, as a result of injection, resemble gneisses and contain eyes of quartz and feldspar, with some mica. These occur near the main granite towards the east. Here also is a characteristic spotted schist con-

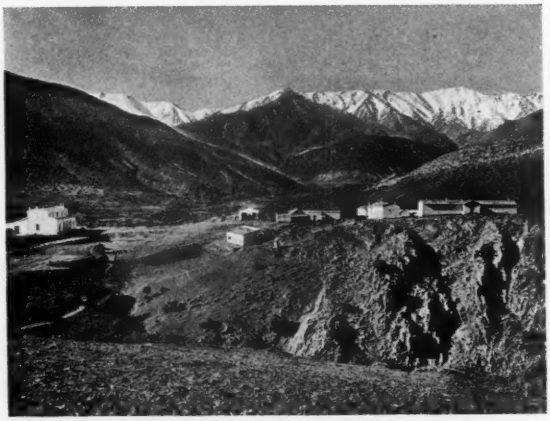

FIG. 2. Mining camp, Azegour, looking south. Houses at right are on the granite. Left foreground, metamorphic (spotted) schists and quartzites. The flat strata of the middle ground are Cretaceous. Snow mountains in background (Djebel, Erdouz, 3,500 M.) are folds of Cambrian strata thrust upon the Cretaceous beds.

taining andalusite, mica, and chlorite. The limestone has in places escaped intense alteration (Fig. 3) but for the most part is strongly metamorphosed into marble or cipolline with hornstones, containing diopside, wollastonite, idocrase, and green, brown, or red garnet. Duparc (4), Grosclaude (11), and Nicolet and Brandenberger (12) also describe a new mineral called duparcite, a distinct green tetragonal variety of idocrase. Garnet or idocrase may even constitute the main part of the rock. Above

the flotation plant the writer found a remarkable rock composed of silky white fibrous crystals of wollastonite 5–10 Cm. in length, associated with small grains of brown garnet (*W*, Fig 1).

The molybdenite, like the other ores, is always associated with garnet, which locally forms the principal constituent of the rock and consequently is here referred to as garnetite. The molybdenite may possibly have gained entry into the rock owing to diminution of volume during garnetization (11). Grosclaude's map (11) shows the irregularity of the garnetite formed within the limestone. The most important zones impregnated with molybdenite are not confined to the contact of the limestone with the schist, or with the igneous dikes, but are found within the limestone body (Fig. 1). The garnet, with more or less molybdenite, is irregular in thickness, ranging from a few meters up to 20 meters.

Ores.—The molybdenite impregnation in garnetite and garnetiferous marble has been followed at the surface for a distance of more than 3.5 Km. within the same limestone formation. The molybdenite commonly forms small scaly grains up to a few millimeters in diameter. In places it occurs in the form of rosettes up to several centimeters or even decimeters in width, and rarely in pockets up to one cubic meter in volume of pure molybdenite (MoS_2).

The average content of molybdenite in 8,000 tons of ore stored at the mine in April, 1932, was estimated at 2 per cent of MoS_2.[3]

The granite batholith has been considered wholly responsible for the contact metamorphism, but this is not correct. For instance, the red dike of microgranulite one meter in thickness at the mining road (*P*, Fig. 1) has metamorphosed the surrounding schist for one-half meter into a pseudo-gneiss, and the adjoining basic dike likewise shows an individual contact aureole. Another basic dike 12 meters thick is in contact with garnetite 4 meters thick. Possibly its mineralization is due partly to this secondary igneous body.

[3] A flotation plant has now been erected.

For the most part, there is no sharp limit between molybdenite-bearing garnetite and adjacent marble or limestone; the garnet and molybdenite gradually disappear. In some places the impregnation seems to be related to tectonic movements. Thus, the garnetite shown in Fig. 1, rich in MoS_2, especially in the upper

FIG. 3. Cambrian limestone with MoS_2 impregnation. Oued Acker, 2 Km. NNE. of Azegour mining camp. Original stratification well preserved, dipping 70° E.

part, is sharply limited above by a fault. Also, the quartz-porphyry dike one to two meters thick which cuts across the garnetite has caused a slight but distinct vertical displacement. Faults, however, do not seem to be of any importance, and apparently have had nothing to do with the mineralization.

Expectations.

According to the latest private information, the Azegour mine since January, 1933, has produced up to 0.75 tons of molybdenite per day, containing 86–90 per cent of MoS_2, from treatment of about 50 to 70 tons of ore. From now on its production may increase and may compare favorably with American records. The ore as mined is expected to contain an average of 1 to 2 per cent of MoS_2 as compared with 0.8 per cent at Climax, Colorado, and 0.5 per cent at Knaben, Norway.

Geologically, the Azegour mine is unique. The molybdenite occurs in the limestone as a result of contact metamorphism, whereas in other molybdenum mines it is in granite, porphyry, or quartz veins. However, in all cases the molybdenum ultimately seems to have been derived from acid igneous intrusions either by pneumatolitic or hydrothermal action.

Zurich, Switzerland.

Bibliography Since 1929.

Morocco.

1. Hébrard, M. F.: Etude sur le gisement de Molybdénite, Cuivre, Blomb et Zinc d'Azegour (Maroc). With geol. map in colors. Ed. Lemeunier Lussan, 47 Bd. St. Michel, Paris, 1929.
2. Duparc, L.: Rapport sur le Gite de Molybdénite d'Azegour (Maroc), fait pour la Soc. Le Molybdène. With geol. map in colors. De Matteis, Paris, 1930.
3. ——: Sur le Gîte de Molybdénite d'Azegour. C. R. Soc. Phys., Genève, vol. 47, No. 2, 1930.
4. ——: Sur les Phénomènes de Contact du Granite d'Azegour et sur les Gisements de Molybdénite. Bull. Suisse de Min. et Pétr., t. 10, 1930.
5. ——: Les Gisements de Molybdénite d'Azegour (Maroc). Congr. intern. des Mines, de la Métallurgie et de la Géologie appliquée, VI. session, Juin, 1930, pp. 75–80. Liège, 1931.
6. Moret, Léon: Recherches géol. dans l'Atlas de Marrakech. Allier Père et Fils, Grenoble, 1931.
7. ——: Carte géol. provisoire de l'Atlas de Marrakech, 1:200,000. Allier Père et Fils, Grenoble, 1930.
8. Heim, Arnold: Observations tectoniques dans le Haut Atlas. C. R. Soc. géol. de France, No. 10, p. 128, 1932.

9. ——: Tektonische Beobachtungen im Hohen Atlas. Verh. Schweizer. Naturf. Ges., p. 345, 1932; and Eclogae geol. Helv., vol. 25, No. 2, pp. 262–263, 1932.

10. DUPARC, L.: Sur les Roches éruptives et métamorphiques d'Azegour (Maroc). Verh. Schweiz. Naturf. Ges., pp. 348–350, 1932.

11. GROSCLAUDE, R.: Etude du Gisement de Molybdénite d'Azegour (Maroc). With geol. map 1:10,000. Thèse. Alb. Kundig, Genève, 1933.

12. NICOLET, S. E., AND BRANDENBERGER, E.: La Duparcite, un nouveau Silicat de Contact. Bull. Suisse de Min. et Pétr., vol. xiii, pp. 222–231, 1933.

OTHER COUNTRIES.

13. BUTLER, B. S., AND VANDERWILT, J. W.: The Climax Molybdenum Deposit of Colorado. Colorado Sc. Soc. Proc., vol. 12, No. 10, 1931.

14. CARMEN, J. B.: Mining Methods of the Molybdenum Corp. of America at Questa, New Mexico. U. S. Bur. of Mines. Inf. Circ. 6514, 1931.

15. LARSEN, E. S., AND ROSS, C. S.: R. and S. Molybdenum Mine, Taos County, New Mexico. ECON. GEOL., vol. 15, pp. 567–573, 1920.

16. VANDERWILT, J. W.: Geology of the Molybdenite Deposits at Climax, Colorado, and of Other Deposits Producing Molybdenite. Amer. Inst. Min. and Met. Eng., New York meeting, February, 1932.

A HYDROTHERMAL DEPOSIT IN WAYNE COUNTY, MISSOURI.

W. A. TARR AND JOSEPH J. BRYAN.

INTRODUCTION.

IT IS generally known that the lead deposits of southeastern Missouri (the "Lead Belt") are in Paleozoic sediments. These deposits occur on the east, north, and west sides of an extensive area of igneous rocks of pre-Cambrian age. Important barite deposits, the only important cobalt-nickel deposit (containing also copper and lead) in the United States, and some small copper deposits also occur near this pre-Cambrian area. Within the igneous area occur the important specular iron deposits of Iron Mountain and other localities, and some small tungsten and silver-lead deposits. The formation of the last-mentioned deposits was accompanied by considerable hydrothermal alteration (greisenization) of the granite country rock.

As any evidence bearing upon the extent of hydrothermal mineralization within the general region is significant, the following brief account of a small, recently (1929) discovered, hydrothermal deposit has been prepared. Although zinc and lead occur, and assays made for the discoverer, Mr. G. F. O'Brien, indicate rather high values in the precious metals, the deposit is of no commercial value. It is of interest chiefly as contributing to a knowledge of the mineralization of this portion of the Mississippi Valley.

Location.—The deposit lies in the central portion of the extreme northern part of Wayne County in southeastern Missouri. It is situated about three and one-half miles southwest of the village of Coldwater, near the St. Francis River, in the S. E. ¼ of Sec. 11, T. 30 N., R. 5 E.

General Geology.—The rocks of the area are pre-Cambrian igneous rocks and early Paleozoic sediments (unrelated to the mineralization). The igneous rocks are a granite (the country

rock of the deposit), rhyolite porphyry, basalt, and aplite. The granite is intrusive in the rhyolite porphyry, and the basalt and aplite occur as dikes cutting the granite. The evidence that the granite is intrusive was found by Tarr [1] in his study of the igneous rocks of the southeastern Missouri region.

The granite near the O'Brien prospect pits is a coarse-grained, slightly porphyritic rock, of a reddish color which ranges in shade from a light flesh tint to a very dark red. The porphyritic crystals of orthoclase (some an inch in length) stand out prominently upon a weathered surface. Quartz is the other abundant constituent seen megascopically. Quartz veins are common in the higher portions of the granite outcrops, where some epidotization also has occurred along the joints. Aside from the porphyritic character, the granite is uniform in texture.

The microscope shows the granite to consist of orthoclase (the dominant mineral), oligoclase, microperthite, microcline, quartz (about 20 per cent.), magnetite, and rarely a little subsequent epidote and chlorite replacing feldspar. The magnetite occurs as small euhedral crystals and grains between the quartz and feldspar. Near the surface of the granite, the feldspar is more or less cloudy with kaolin.

The basalt of the dikes is black, or very dark green, and fine-grained. Three or four dikes occur in the vicinity of the altered area; one, 15 to 20 feet wide, has a course approximately N. 45° W., and two other smaller ones, close to the deposit, strike nearly north and south, which is the direction of the major joint system of the area. The aplite dikes range from 1 to 10 inches in width, and are much more common than the basalt dikes.

Structure.—The granite is massive throughout the area. The most significant structural feature is a sheeted zone striking nearly north and south, the joints of which are from one-half inch to five or six inches apart. Faulting has occurred along the zone, though whether in more than one period it is impossible to say. The hydrothermal alteration occurred in or along this sheeted zone.

[1] Tarr, W. A.: The Intrusive Relationship of the Granite to the Porphyry (Rhyolite) of S. E. Missouri. Bull. Geol. Soc. Amer., vol. 43, pp. 965–992, 1932.

THE MINERALIZATION OF THE AREA.

Five periods of mineralization occurred in the area; all apparently independent, though the second and third periods may overlap to some extent. They are:

1. The formation of the quartz-pyrite veins.
2. The hydrothermal alteration.
3. The sulphide phase.
4. The introduction of magnetite and orthoclase.
5. The formation of quartz-microcline veins.

Figure 1 shows the sequence of the minerals in the deposit and indicates their relative abundance.

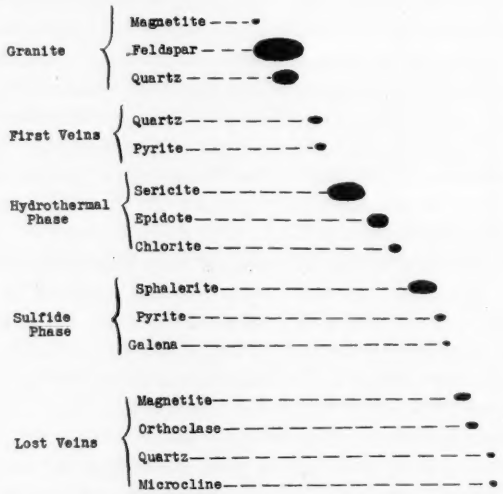

FIG. 1. Sequence of the minerals found in the deposit.

Quartz-pyrite Veins.—The quartz-pyrite veins in the granite range from four inches to a fraction of an inch in width. Quartz is the dominant mineral in them, the pyrite rarely amounting to five per cent. The pyrite is so light in color that tests for arsenic were made to prove that it was not arsenopyrite. The veins con-

tain a few grains of fluorite, also. Quartz was the first mineral deposited in the veins, but during the closing stages of deposition the two minerals formed simultaneously. Crystal faces on some of the pyrite indicate a rapid growth during a pause in the deposition of the quartz. These veins cut the fresh granite, and apparently their formation caused no change in the wall rock. They, like the other phases of mineralization, are confined to the sheeted granite.

Hydrothermal Alteration.—The most interesting part of the mineralization of the area is the intense hydrothermal alteration of the granite. The alteration is confined to three areas, all of which occur within 500 feet of one another along the sheeted zone. Small prospect pits (one is 25 feet deep) have been opened in all of them. The hydrothermally altered areas extend variable distances from the joints, though rarely more than two feet. The contact between the granite and the altered material is irregular. The altered mass may grade into more or less epidotized granite, or it may have a sharp contact with slightly altered granite.

The mineralization is remarkable because of the almost complete alteration of the granite to sericite, epidote, and chlorite (Fig. 2). A hand specimen of the altered rock is dark green, with the light-brown color of the sphalerite scattered through it. The great abundance of mica (and some chlorite) gives the rock a luster resembling that of a schist. Fragments of residual grains of feldspar, quartz, and magnetite are commonly seen in thin sections of the highly altered granite. The residual magnetite can be distinguished from the later magnetite which was deposited by the hot solutions by the fact that the former is surrounded by a creamy white mass of leucoxene. The younger magnetite is perfectly fresh and unaltered. The two generations of magnetite may occur side by side.

The first mineral formed during the alteration was the *sericite,* then the *epidote,* and lastly the smaller amount of *chlorite* (Fig. 2). The abundance of well crystallized *sericite* (*S,* Figs. 2 and 5) indicates that the first alteration was an intense phase of sericitization. In some portions of the deposit, all of the original feldspar and most of the quartz are gone. Here and there, how-

ever, are feldspar remnants surrounded by sericite (S, in Fig. 2). The sericite occurs as fibrous and radiating aggregates (Fig 2), and shows the usual optical features. The original granite consisted of 50 to 65 per cent. orthoclase and microcline, and, as these

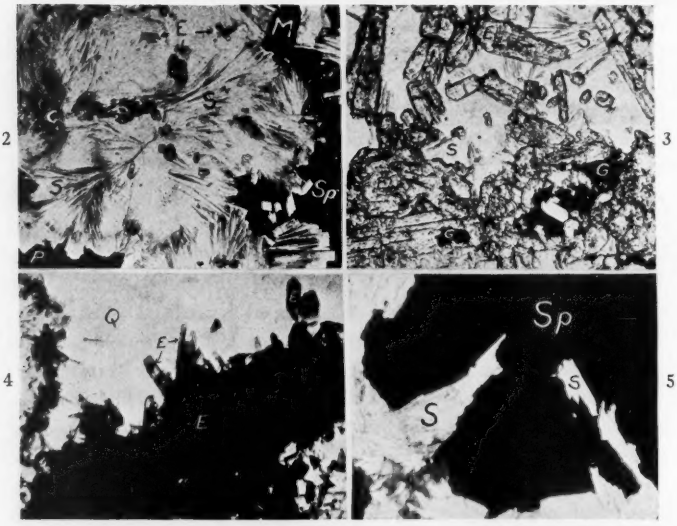

FIG. 2. Photomicrograph of hydrothermally altered granite. S = sericite; E = epidote; C = chlorite; P = pyrite; Sp = sphalerite; M = magnetite. Ordinary light, × 85.

FIG. 3. Photomicrograph showing epidote (E) replacing sericite (S), and galena (G) replacing epidote. Ordinary light, × 85.

FIG. 4. Photomicrograph showing epidote (E) crystals replacing quartz (Q). Ordinary light, × 30.

FIG. 5. Photomicrograph showing sphalerite (Sp) replacing sericite (S). Polarized light, × 85.

minerals contain 16 per cent. potash, it is not surprising that so much sericite should now be present. The formation of the sericite did not involve the introduction of much material, as the abundant feldspar furnished everything needed except the water which was supplied by the solutions. The solutions did not pene-

trate far into the surrounding granite, as no sericite is found further than a few feet from the sheeted zone.

The term *epidotization* is used here because of the abundant development of epidote (*E*, Fig. 3), not only in the vein deposit, but also, though to a lesser degree, in the granite. The epidote, unlike the sericite, would require the introduction of iron and calcium for its formation, although the limited amount of plagioclase present would contribute some of the calcium.

The amount of iron required for the formation of epidote varies widely, as it is isomorphous with the aluminum. The actual ranges in iron and aluminum are shown in the following lists, which give the percentages of the two oxides in epidotes. (Analyses are from Dana's System of Mineralogy.)

Al_2O_3	Fe_2O_3
33.71	——
27.23	8.53
25.98	10.18
24.13	12.60
21.13	16.55
——	44.35

The epidote represented by the first of these analyses was a colorless mineral. With the increase in iron content, the epidotes represented by the other analyses were increasingly darker.

The epidote in the deposit under discussion was evidently iron-poor, for it is light colored. Such an epidote requires a larger amount of calcium for its formation than do the iron-rich varieties. The large amount (about 50 per cent., although this is not the average amount) of epidote (*E*, Fig. 3) in some parts of the vein material indicates that both iron and calcium were undoubtedly added by the hot solutions. Where a determination of the original feldspar was possible, it was found that the epidote formed first in the oligoclase. Later, however (and especially in the highly altered vein material), epidote replaced sericite (*E* and *S*, Figs. 2 and 3) and quartz (*E* and *Q*, Fig. 4). The crystals of epidote which penetrate quartz are well shown in Fig 4. From the largest of the prospect pits, material was obtained that con-

sists of practically nothing but epidote, so complete had been the alteration.

On the whole, there is only a small amount of chlorite (*C*, Figs. 2 and 3) in the vein material, but locally it may amount to 15 or 20 per cent. Its formation in the deposit required the introduction of magnesium, as there were no magnesium minerals in the original rock. Ferrous iron occurs in chlorite; so, as the small amount of magnetite in the rock would not have furnished it in sufficient amount, iron, also, must have been brought in by the solutions. Chlorite was formed from feldspar, epidote, and sericite.

Sulphide Phase.—Sphalerite (with a little pyrite and galena) was introduced during the closing stages of the hydrothermal alteration. None of these minerals show well developed crystal forms; they occur as irregularly shaped masses and grains replacing all the previously formed minerals. A partial analysis of the vein material (the so-called "ore") shows 6.78 per cent. of zinc. This would be equivalent to 10.12 per cent. of sphalerite.

The sphalerite is scattered all through the ore. It encloses long shreds of sericite (*S*, Fig. 5), which it seems to have replaced more readily than epidote. Small grains of pyrite occur both within and at the edges of the sphalerite areas; hence the pyrite may have been formed at the same time or a little after the formation of the sphalerite. The pyrite grains also occur replacing the other minerals of the vein. The few grains of galena present are later than the sphalerite, and may or may not replace it. This sequence in the sulphides is essentially the same as that found by Singewald and Milton [2] at the old silver mine about 25 miles north of this locality.

Magnetite and Orthoclase.—Thin veins of magnetite and orthoclase represent the closing stage of mineralization, as they cut both the granite and the ore. They are filled-fissure veins, and are rarely one-half inch thick. They include small frag-

[2] Singewald, J. T., Jr., and Milton, Charles: Greisen and Associated Mineralization at Silver Mine, Mo. ECON. GEOL., vol. 24, pp. 588–589, 1929.

ments of the ore. The magnetite was deposited first, but the deposition of the orthoclase began soon afterward.

This phase of the mineralization was preceded, in some parts of the ore, by the formation of a magnetite that replaces both silicates and sphalerite. This magnetite was probably introduced through the fissures which were later filled with magnetite and orthoclase, but proof of this is lacking. The magnetite penetrating the ore replaced any of the silicates but usually the chlorite, whereupon it assumed the radiating, bladed form of the chlorite. In some portions of the ore, this magnetite had been oxidized to a deep red hematite (martite), retaining the same bladed form as the pseudomorphic magnetite. The magnetite in the sericite and in some of the other minerals is euhedral. Remnants of feldspar have been replaced along the cleavage planes. The magnetite has replaced the sphalerite—a rather uncommon occurrence.[3] The replacement has occurred in varying degrees; in some grains, a little magnetite has slightly penetrated the sphalerite, darkening it and making it magnetic; in other grains, it has wholly replaced the sphalerite. The magnetite, however, more often replaced the silicates. The appearance of the magnetite at this late stage in the mineralization is probably due to a resurgence of solutions from below, as magnetite belongs to the higher-temperature periods of mineralization.

Quartz-microcline Veins.—The laboratory examination of the material from the deposit revealed the presence of thin (1/16 inch in thickness) veins of well crystallized quartz and microcline. They are filled-fissure veins that cut the ore, but their relationship to the other phases of mineralization is unknown. The appearance of well crystallized microcline in a vein is a very interesting occurrence of this mineral.

ORIGIN OF THE DEPOSIT.

The minerals of this deposit and the character of the alteration of the granite are such as to leave no doubt that hot waters from

[3] Bastin, E. S., and others: The Criteria of Age Relations of Minerals. ECON. GEOL., vol. 26, p. 588, 1931.

an underlying source brought about the mineralization. The first solutions to work their way outward deposited the quartz-pyrite veins and did not alter the country rock. Later, hot and active solutions worked their way upward along the sheeted zone in the granite, converting it near the joints into a mass of sericite, epidote, and chlorite. During this stage, the solutions carried some calcium, magnesium, and iron (largely in the ferric state). After the completion of this phase of the alteration, solutions carrying an abundance of zinc and sulphur, with some iron and lead, deposited the sulphides. The solutions during this hydrothermal phase were hot, but they do not appear to have contained many mineralizers. Rather, it seems that they followed the sheeted zone upward,—nearly to the upper part of the granite mass, where their confinement and increased concentration brought about the intense but local alteration. The next part of the mineralization involved the introduction of the magnetite replacing the silicates and sphalerite of the hydrothermal phase, and the formation of the magnetite-orthoclase veins. The solutions that deposited these minerals were evidently hot and probably represented a resurgence from below. Though the quartz-microcline veinlets were formed later than the ore, it was impossible to determine their relationship to the later phases of mineralization.

The mineralization of this deposit, although it has some of the features of the greisenized deposit farther to the north, lacks several of the minerals (such as topaz, wolframite, cassiterite, and fluorite) typical of a greisenized deposit. The intense development of epidote and the abundance of sphalerite and magnetite give this deposit characteristic features of its own. There can be little doubt that the alteration was due to magmatic waters. Presumably, the time was pre-Cambrian.

UNIVERSITY OF MISSOURI,
COLUMBIA, MO.

DISCUSSION AND COMMUNICATIONS

HOW TO DETERMINE PROBABLE CHANGES IN PRIMARY MINERALIZATION WITH INCREASING DEPTH.

Sir:—In veins that are filled by deposits from ascending magmatic solutions, changes in mineralization with increasing depth may be predicted by establishing the succession of minerals (1) in wide fissures, or (2) in successively deposited veins, or (3) by determining the composition of deposits belonging to the same magmatic source but deposited at different distances from it.

1. As the mineral-bearing solution from the parent magma becomes cooler, its deposits on the walls of the veins change accordingly. The same or a similar change takes place in depth

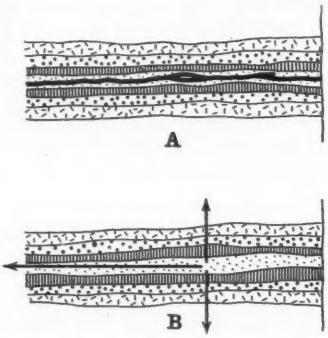

FIG. 1.

corresponding to the increase of temperature with depth. In such veins, the change in mineral composition as depth increases corresponds to the change from the youngest to the oldest, or from the center of the vein to the walls (Fig. 1, A and B).

Obviously, changes are slower as the igneous source is approached; also irregularities may be produced by changes in the velocity of ascending solutions, by heating the wall rock, or by chemical or physical characteristics of the country rock.

2. It may be assumed that the difference in composition of the vein filling of successively opened fissures is due to the reduction of temperature and the change in the mineral content of the solution between successive fissure openings.

If one can establish the succession of minerals deposited in successively opened fissures, the mineral succession with increasing depth can be determined. It may be assumed that the changes in composition from the youngest mineral to the oldest in the succession of veins correspond to the changes with increasing depth.

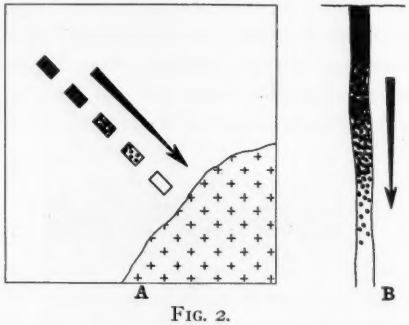

FIG. 2.

3. In mineralized zones originating from large intrusive bodies, a whole series of different ore deposits is often developed. The deposits nearest to the parent magma are commonly those whose mineral content is developed at higher temperatures; those developed at greater distances, on the contrary, are characterized by minerals that develop at lower temperatures.

It follows, therefore, that if we determine the mineral composition of different ore deposits belonging to the same magmatic source and establish the changes in mineral composition between the farthest developed and those nearest to the magmatic source,

we may with good reason assume that similar changes take place in depth, as illustrated in Fig. 2, A and B.

BOHUSLAV STŎCES.

VSOKÉ, SKOLY BANSKÉ,
PŘÍBRAM, CZECHOSLOVAKIA.

DIATOMACEOUS EARTH IN OREGON.

Sir:—In the December, 1932, issue of your journal, there is an article, " Diatomaceous Earth in Oregon," by W. D. Smith. On page 709, fifth paragraph, appears an extract from my monograph on diatomite [1]:—" Luster—dull; Sp. Gr. 2.1–2.2 at 25° C." An important omission here is the word *true*. The quotation should read, " Its *true* specific gravity or density is 2.1 to 2.2. at 25° C." On the next page, first paragraph, the author states that the sp. gr. of the Harper diatomite is 1.25, and a few lines down he remarks, " There is one considerable discrepancy in these figures, namely the sp. gr., which in the case of Wilmot's seems clearly to be in error."

Our Chemical Division has ascertained the true specific gravities of a number of diatomites from different parts of the world, finding them to be always more than 2.0. Recently 8 different diatomites were tested, including the best quality crude Harper material, and we found the true specific gravities to vary between 2.10 and 2.22, the lighter being the crude and the heavier the calcined diatomites. The Harper diatomite was 2.10, quite comparable to pure opal. The method briefly consists of vigorously boiling the sample (previously dried at 105° C. for 12 hours) in distilled water, settling for 24 hours under vacuum, and weighing in the water at 15° C.

It appears probable that when the tests were conducted by the Oregon Dept. of Geology, the entrapped air may not have been all excluded before the final weighings, also the samples were perhaps not bone-dry immediately before testing.

It is perhaps injudicious for one scientific writer to say of another that his statement " seems clearly to be in error " unless such statement has been carefully re-checked.

[1] Can. Dept. Mines Bull. 691, 1928.

Incidentally I wish to point out that it is unfortunate to continue the use of the term diatomaceous *earth,* as this is not correct, particularly in referring to a deposit such as the one at Harper. Substitute "silica" if necessary, but preferably keep to "diatomite."

It would be interesting to know what meaning the author intends to convey by his remark at the bottom of page 709 as to the increase in the addition of 10 per cent. diatomite.

I personally visited and examined the Harper deposits in 1930. The author in his description of the structure (bottom of page 707) refers to minor faults and small displacements, but omits that which is very important from a mining and quarrying standpoint, namely, the vertical displacements of huge masses. I have, for example, photographs showing two successive drops of 50 feet each of the same series of beds, totalling over 100 feet vertical displacement. With the aid of a barometer and by a careful study of certain distinctive beds or "horizon markers," even greater displacements were noted within the area of a few square miles.

V. L. EARDLEY-WILMOT.

MINES BRANCH,
OTTAWA, CANADA.

REVIEWS

Ein deformiertes Flussspat-Quarz-Kupferkiesgefüge aus einer mittelschwedischen Sulfidlagerstätte. By DORIS KORN. Neues Jahrb. für Min., etc., B. B. 66, Abt. A, pp. 433–459, 1933.

The material examined in this study came from a deformed sulphide ore body at Yxsjö, in central Sweden. The investigation was undertaken for two reasons: in the first place, to study the mechanism of the tectonic deformation of fluorite, about which nothing has been hitherto known; and in the second place, to compare the results of a fabric analysis of the ore with the conclusions concerning the relative age of the replacement minerals that were based on the microscopic texture. The textural relations of minerals is no clear proof of their relative age if the material in which they occur has been strongly deformed, a fact which is even more true in the study of ores than of non-opaque minerals because most ore minerals yield more readily to deformation than most non-opaque minerals.

The sulphide ores of central Sweden occur principally in the leptites and included skarns that are limited to zones of tectonic disturbance. The ores are localized along planes of mechanical discontinuity, such as foliation planes, surfaces of slip, contact surfaces, and planes of shear, because there the ore-bearing solutions find easiest passage. From these surfaces the metasomatic replacement progresses outward. It is a striking feature that the mineralization is strong in leptites and pegmatites that occur in cataclastic zones, although in many places it has failed to affect the much more susceptible limestones that lie near the ore body but outside the cataclastic zone. The deformation recorded in both rocks and ore is postcrystalline, which means that the deformation continued after the mineralization had ceased.

Apparently the original constituents of the rock were quartz, mica, calcite, and actinolite. The ores consist of pyrite, pyrrhotite, sphalerite, and chalcopyrite associated with scheelite, fluorite, and molybdenite in typical pneumatolytic paragenesis. The material investigated came from skarn layers in the leptite. Both in the hand specimen and in thin section the ores show a strongly deformed fabric, so that the problem involved is the determination of the relative age of the minerals and the history of the ore formation in a rock where ordinary criteria fail on account of the deformation.

Microscopic study reveals a distinct parallel arrangement of the opaque and non-opaque constituents. Most of the non-opaque minerals are fluorite and quartz with subordinate white mica, actinolite, and a few isolated grains of calcite that remained after the greater part of the mineral had been replaced by fluorite and chalcopyrite. Striated fluorite forms a fine-grained matrix inclosing quartz in bands and in lenticular aggregates, whose longest axes are parallel to the striations in the fluorite and to the arrangement of the sulphides. The most abundant opaque mineral is chalcopyrite with minor sphalerite, a little molybdenite, and decomposed pyrite. The fluorite is penetrated by chalcopyrite particles in parallel arrangement, and euhedral fluorite is partially surrounded by embayed quartz. From the microscopic study it might be inferred that the original constituents of the rock, quartz, calcite, mica, and actinolite, have been subjected to pneumatolytic replacement by fluorite and chalcopyrite. Therefore a comprehensive study of the rock fabric was undertaken in order to see how far the above conclusion would be confirmed by a complete synthesis of the various movements that have affected the original rock and the ore replacement.

The parallel structure (s-surfaces in the terminology of Sander) shows between the layers of fluorite and of actinolite a well-marked undulation that can be recognized in both directions transverse to the s-surface. In addition to these s-surfaces the rock fabric shows numerous cracks that appear at first sight to have irregular distribution. However, when the poles of these cracks were platted upon a projection similar to the preferred orientation diagrams, it was seen that they fall into two separate systems and can be related to two distinct strains.

Conclusions drawn from the study of the orientation in the mineralized rock are based upon the fact that the symmetry of a rock fabric reflects the vectorial symmetry of the motion accompanying the formation of the fabric. Where the motion is postcrystalline, it is clearly one of deformation subsequent to the formation of the constituent parts of the fabric; where it is paracrystalline the motion has accompanied the formation of the constituents.

The differential motion during tectonic deformation is co-ordinated to the axes *a*, *b*, and *c* established by the recognition of an s-plane containing the axes *a* and *b* and by the determination of a linear direction (axis B) in the s-plane. In these rocks the s-surface can be recognized megascopically by the banded arrangement of the quartz and hornblende and by the striations in the fluorite and the parallel arrangement of the chalcopyrite particles. The linear direction B is recognized by the linear arrangement of the hornblende crystals in the s-surface. The *a*-axis is by definition the direction of movement along the *ab* plane and the *c* axis is the normal to the *ab* plane.

If the direction of movement does not remain constant during the course of deformation, obviously there will be a rotation of these *a*, *b*, *c* axes. Such a rotation may be produced either by superimposition of movements that take place at different times or by the same act of movement with a change in the direction of movement during the act. The undulation in the s-surfaces of the rocks is the megascopic evidence of such displacement in the axes of motion. The fabric analysis, carried out by the use of a Federov stage, throws much additional light on the process of deformation.

By preferred orientation analysis Miss Korn studied the partial fabrics [1] of mica, actinolite, quartz, fluorite, and chalcopyrite; and the result of the partial fabric analysis was synthesized into a complete history of the movements by which the fabric as a whole came into existence.

The conclusions reached by the fabric study can be summarized as follows.

I. Fluorite responds to the movement resulting from tectonic stress by rotating until individual grains are in such a position relative to the major slip plane of the movement that they can deform by twinning on an octahedral plane, the displacement being a dodecahedral direction. This study of fluorite does not indicate that the translation along a cubic gliding plane that was produced by Veit's experiments played any part in the tectonic deformation.

II. By establishing the preferred orientation of the individual constituents and thus determining the partial fabrics that make up the rock fabric as a whole, it is possible to show that the deformation has taken place by movement in response to two different stresses. The fabric of the quartz, mica, and actinolite conforms to the symmetry of the first movement with modifications produced by the symmetry of the second movement. The fabric symmetry of the fluorite and chalcopyrite is quite different and shows none of the orienting influence of the first movement.

Such a change in the symmetry of fabric in different constituents can be explained in two ways:

1. The constituents may have all been subjected to the orienting influence of one movement that changed its direction during its progress.

2. The constituents may have been subjected to the orienting influences of two movements having a different symmetry and separated from each other by a period of rest (relaxation of movement). The fact that certain constituents show the imprint of only one movement may be explained by their ready susceptibility to rearrangement so that the second movement has completely stamped out the evidence of the first deformation. On the other hand, these constituents may have been formed later than the first deformation.

[1] A partial fabric is the fabric of one constituent in a polymineral aggregate.

The second explanation appears to be most probable for the Swedish sulphide ores, because a careful study of the preferred orientation of the cracks that characterize the fabric shows two systems of cracks conforming in their symmetry to (1) diagonal (shear) cracks and (2) cross (tension) cracks belonging to different deforming movements. The earlier system, formed in the lenticular quartz aggregates during the first phase of deformation, has apparently been healed by the pneumatolytic mineralization. A differently oriented system of cracks was then developed in conformity with the axes of the second deforming motion, and thus in a definite relation to the preferred orientation of the fluorite and chalcopyrite. As the quartz, feldspar, and mica show both the relict imprint of the preferred orientation caused by the first deforming movement and also the partial overprint of the second deforming influence, it is probable that the fluorite and chalcopyrite, which show only the imprint of the second deformation, were never exposed to the first deformation, but were deposited after the deformation of the earlier constituents had ceased. This conclusion fully supports the mineral sequence that can be deduced from the texture of the ores.

The paper is succinct and clearly written and is an interesting example of the possibilities for detailed investigation of the history of ore deposition that have been opened up by the statistical study of the preferred orientation of rock minerals.

ELEANORA BLISS KNOPF.

Minerals and the Microscope. 3d Ed. By H. G. SMITH. Pp. xiii + 124. Pl. 12, figs. 33. Thos. Murby and Son, London, 1933. Price 5 s.

The new edition of this popular little book differs from the earlier editions mainly in its treatment of rocks, the chapters on which have been entirely rewritten to include the new ideas that have been developed in petrology since 1919, the date of the 2d edition, emphasis being placed upon differentiation and assimilation theories to account for the variations in rock types, and upon rock classification.

Elements of Optical Mineralogy. By A. N. WINCHELL. 3d Ed. Part II, Descriptions of Minerals. Pp. 459, figs. 361. John Wiley and Sons, New York, 1933. Price, $6.00.

In the six years that have elapsed since the appearance of the second edition of this internationally known text, there has been significant development in optical mineralogy. This new edition continues the general purpose and arrangement of the previous editions. It presents descriptions of minerals with special reference to their optical and microscopic identification, arranged according to the Dana classification. In addition,

the newer classification for silicates, based on x-ray studies, has been adopted; new correlations and diagrams resulting from the relations between optical properties and chemical composition have been incorporated; new minerals have been added; and the section on amphiboles has been mostly revised.

The volume is the most complete and handy reference of its kind available, and should continue to fill the field of its worthy predecessors.

An Introduction to the Study of Fossils. By H. W. SHIMER. Revised edition; pp. 496, figs. 207. Macmillan Co., 1933. Price, $4.00.

Like its well known predecessor, this edition deals systematically with plants and animals, both living and fossil, in terms as non-technical as possible. There are revisions in classification and added summaries of the relationship and evolution of phyla and classes, and of the contributions of each phylum in rock building. It is a readable, up-to-date text.

Great Men of Science. By PHILIPP LENARD. Translated from the German by H. S. HATFIELD. Pp. 398. Macmillan Co., New York, 1933. Price, $3.00.

Professor Lenard, himself a physicist of international fame and a Nobel Prize winner, is eminently fitted to write about the great men of science. He tells in vivid language of the lives and work of more than fifty outstanding scientists of all nationalities, each of whom has contributed some new idea of major scientific importance. He makes them living figures, and their tasks and successes are not merely chronological history. Starting with Pythagoras, his discussions of the men form a development of scientific thought up to the present. It is an interesting book for the serious reader.

BOOKS RECEIVED.

By

DAVID GALLAGHER.

Geological Survey of Great Britain and Museum of Practical Geology: Summary of Progress, 1932: Pt. II. London, England. Price, 3s. and postage. Summary of results of study of the geology of the Meneage; the Kent coalfield; the Gault of Cambridgeshire; a composite auto-intrusion of a Carboniferous lava flow; also descriptions and illustrations of lower Ordovician graptolite faunas and the fauna of Paleozoic rocks traversed by a deep boring near Little Missenden, Bucks.

Canada Geological Survey, Index to Bulletins, 1913–1926; Memoirs, 1910–1926; Summary Reports, 1917–1926; Sessional papers, 1921–1926. Compiled by FRANK NICOLAS. Pp. 666. Geol. Surv. Can. No. 2260, Ottawa, 1932. Price, $2.00 (paper). A complete combined subject, author, and locality index of the Survey publications for the years indicated above.

Geological Survey of England and Wales: maps, Clossop Sheets No. 86, 1932. One colored sheet showing hard geology, another showing in addition the drift deposits. The area is underlain by Upper Carboniferous beds, including a small part of the Middle Coal Measures. Scale = 1 inch to 1 mile.

Gold in Canada, 1933. By A. H. A. ROBINSON. Pp. 92, tables 39, figs. 8. Canada Dept. Mines, Mines Branch, No. 734. Ottawa, 1933. 20 cents. Brief descriptions of the history, organization, development, geology, and production of the gold mines of Canada.

Tanganyika Geol. Survey, Annual Report, 1932. Pp. 40, figs. 1. Dar es Salaam, 1933. Price, 2/50s. Account of activities and progress for the year.

Provisional Geological Map of Tanganyika, with Explanatory Notes. By E. O. TEALE. Pp. 34. Tanganyika Geol. Surv. Bull. 6. Dar es Salaam, 1933. Price, 4/. The geological map is in full color, about 24 in. × 24 in., scale 1 : 2,000,000.

Report of the Hawke's Bay Earthquake, Feb. 3d, 1931. Pp. 116, figs., maps. Dept. Sci. and Indust. Research, Bull. 43. Wellington, N. Z. 1933. Price 2/. Various portions of this detailed report are written by F. R. Callaghan, J. Henderson, S. W. S. Strong, P. Marshall, C. E. Adams, M. A. F. Barnett, R. C. Hayes, A. Brodie and A. G. Harris.

Gold-bearing Conglomerates of Central Otago (New Zealand). By E. O. MACPHERSON. Pp. 12, figs. 6. Dept. Sci. and Indus. Research, Bull. 40. Wellington, N. Z., 1933.

Copper Deposits in the Squaw Creek and Silver Peak Districts and at the Almeda Mine, Southwestern Oregon, with Notes on the Pennell-Farmer and Banfield Prospects. By P. J. SHENON. Pp. 35, pls. 6, maps 5. U. S. Geol. Surv. Circ. 2. Washington, 1933.

Iron Ore in the Red Mountain Formation in Greasy Cove, Alabama. By E. F. BURCHARD. Pp. 49, pl. 1, figs. 5. U. S. Geol. Surv. Circ. 1. Washington, 1933.

Origin of the Anhydrite Cap Rock of American Salt Domes. By M. I. GOLDMAN. Pp. 32, pls. 18. U. S. Geol. Surv. Prof. Paper 175–D. Washington, 1933. Price, 15 cents.

Schwefel—Graphit—Jod—Bor—Magnesit—Talk. By O. STUTZER, W. WETZEL AND A. HIMMELBAUER. Pp. 396, figs. 106. Die Wichtigsten Lagerstätten der "Nicht-Erze," Band V., by O. STUTZER. Gebrüder Borntraeger, Berlin, 1933. An exhaustive account of each of these non-metallics, including theoretical analysis and description of the geological occurrence and origin, descriptions of the occurrences throughout the world, production data, and excellent bibliographies of each.

Slate in Pennsylvania. By C. H. BEHRE, JR. Pp. 400, pls. 70, figs. 89, 5 maps in color. Penn. Topog. and Geol. Surv. Bull. M 16. Harrisburg, 1933. A very complete and comprehensive treatise on slate, covering all the scientific and technical phases of the subject, together with detailed descriptions of the geology, technology and production practice of all the Pennsylvania occurrences.

Occurrence and Physical Properties of North Carolina Marble. By J. L. STUCKEY AND J. FONTAINE. Pp. 24. Bull. 5, Eng. Exp. Sta., Univ. North Carolina. Raleigh, 1933. Price, 20 cts.

Problems of Iron Ore Concentration. By T. M. BRODERICK AND F. J. TOLONEN. Pp. 23, figs. 10. Michigan College of Mining and Technology, New Series Bulletin, Vol. 6, No. 4. Houghton, 1933. Application of geology to problems of iron-ore concentration, and gravity concentration tests on Michigan iron formations.

The Pleistocene of the Toronto Region. By A. P. COLEMAN AND F. B. TAYLOR. Pp. 69, figs. 17, colored geological map. 41st Ann. Rpt. Ontario Dept. Mines vol. XLI, Pt. VII, 1932. Toronto, 1933.

Erosion and Sedimentation at Point Pelee. By E. M. KINDLE. Appendix on Beach Protection and Reclamation, by W. R. ROGERS. Pp. 29, figs. 22, map. 42d Ann. Rpt. Ontario Dept. Mines vol. XLII, Pt. II, 1933. Toronto, 1933.

Copies of books mentioned under "Reviews" or under our "New Book List" (see advertisement page) may be purchased through our Journal Bookshop by writing to W. S. Bayley, University of Illinois, Urbana, Ill.

SOCIETY OF ECONOMIC GEOLOGISTS

The Fourteenth Annual Meeting of the Society was held, in conjunction with the Geological Society of America, at the University of Chicago, December 28–30, 1933.

The address of the retiring President, Edson S. Bastin, entitled: "The Native Silver Ores" was delivered on December 28th, following which, the annual business meeting was held.

New Officers.—W. E. Wrather assumed office as President for 1934 and Per Geijer as First Vice-President. The following were declared elected upon report of the mail ballot: Otto Stutzer, President for 1935; Edward Sampson, First Vice-President for 1935; F. F. Grout, K. C. Heald and W. B. Heroy, Councilors for 1934–36. The following were elected Regional Vice-Presidents: Leopold Reinecke, for Africa; Takeo Kato, for Asia; E. C. Andrews, for Australia; Hans Schneiderhöhn, for Europe; C. W. Knight, for North America; Eugene Stebinger, for South America.

New Members.—The following new members were elected: J. A. Allan, Edmonton, Alberta; M. B. Baker, Kingston, Ontario; L. V. Bell, Quebec, P. Q.; Alfred Brammall, London, England; Eugene Callaghan, Washington, D. C.; E. H. Davison, Camborne, Cornwall; J. S. De Lury, Winnipeg, Manitoba; A. L. Du Toit, Johannesburg, South Africa; J. L. Fearing, Jr., New York, N. Y.; G. Gordon Suffel, Noranda, Quebec; M. W. Hayward, El Paso, Texas; F. R. Koeberlin, Santiago, Chile; A. H. Koschmann, Washington, D. C.; Rudolf Krahmann, Johannesburg, South Africa; J. G. L. McCrea, South Porcupine, Ontario; A. W. Pinger, Franklin, N. J.; R. E. Rettger, San Angelo, Texas; P. J. Shenon, Washington, D. C.; Q. D. Singewald, Rochester, New York; A. K. Snelgrove, Princeton, N. J.; C. E. Stott, El Paso, Texas; J. L. Stuckey, Raleigh, N. C.; C. A. Sussmilch, Sydney, New South Wales; W. H. Triplett, Monterey, N. L., Mexico; W. L. Whitehead, Cambridge, Mass.; Alexander Zavaritsky, Leningrad, Russia.

Program.—Twenty papers were presented at three afternoon sessions, the titles of which have been mailed to the membership.

New Committees: Program Committee for 1934: W. H. Newhouse, Chairman, W. B. Heroy and George M. Schwartz.

Committee on Award of the Penrose Medal: Edson S. Bastin, Chairman, Sydney H. Ball, F. W. DeWolf.

Thomas B. Nolan was appointed representative of the Society in the Division of Geology and Geography of the National Research Council for the three-year term, July 1, 1934 to June 30, 1937.

W. B. Heroy was appointed representative of the Society to the Council of the Geological Society of America.

SCIENTIFIC NOTES AND NEWS

F. L. Ransome, professor of economic geology in the Balch Graduate School of Geological Science, California Institute of Technology, Pasadena, has been elected by the Geological Society of London as one of its foreign correspondents.

Arthur Notman has severed his connection with the National Recovery Administration.

William Burns, of Duxbury, Mass., was engaged during last summer in the examination of gold prospects in Labrador.

Waldemar Lindgren was awarded the Penrose Medal of the Geological Society of America at the banquet held in connection with the annual meeting at Chicago on December 29. The presentation was made by Professor E. S. Bastin.

Chester K. Wentworth has been appointed Geologic Engineer by the Honolulu Board of Water Supply, and will make detailed studies of the potential water supply for Honolulu. He has been granted indefinite leave of absence by Washington University and will reach Hawaii early in February.

Rollin Farmin has resigned from the International Smelting Company, Eureka, Utah, to join the staff of the Idaho Maryland Mines Company, Grass Valley, Calif.

David C. Sharpstone has been engaged in developing mining properties at Mountain City, Nevada, on what may prove to be extensions of the Rio Tinto ore body.

John E. Penberthy recently left the Belgian Congo en route for the United States.

W. L. Whitehead, of the Mass. Institute of Technology, Cambridge, Mass., recently examined gold properties on the Mother Lode in California.

Thorold F. Field, of Duluth, Minn., has been investigating gold properties in Australia.

William J. Millard has left the firm of Huntley and Huntley, of Pittsburgh, Pa., and is doing independent consulting work in South America and the United States.

Fred Searls, Jr., is president of the newly organized Graniteville Gold Mining Company, for the development of the Rocky Glen and Spottiswood claims, northern Nevada County, Calif.

Stanley C. Herold, of Los Angeles, Calif., has been making an extended trip in Russia, during which he examined the Grozny and Baku oil fields and planned for their development by the Soviet Government.

C. W. Wright, C. F. Jackson, and F. W. Lee, of the U. S. Bureau of Mines, are examining mineral properties in Porto Rico in order to advise the Government regarding development methods and the possibility of geophysical prospecting for iron ore.

George Barbour delivered a series of three lectures dealing with geological and physiographic subjects, at Queen's University, Kingston, Ontario, in December.

Arthur D. Storke, managing director of Roan Antelope, Rhodesian Selection Trust, and Mufulira copper mines, has returned to London after some time spent in inspection of the properties.

The International Congress of Geography will meet in Warsaw, on August 28 to 31, 1934. There will be seven extended excursions in connection with the Congress. Enrollments should be sent to the Secretariat of the Congress, Rakowiecka 6, Warsaw.

The 46th Annual Meeting of the Geological Society of America at Chicago, December 28–30, received a large representation from the Middle West and a sparse one from the East. A group of excellent general papers were heard during the morning sessions, particularly noteworthy being the symposium on the Yellowstone-Beartooth-Bighorn region. During two afternoons the usual sectional papers were heard. The Paleontological and Mineralogical Societies and the Society of Economic Geologists held simultaneous technical sessions. President Leith's address on The Pre-Cambrian was a broad general review of the investigations, problems, and possible future trends of this complex subject. The smoker and banquet were successes; at the latter the speeches were brief, and interesting movies relating to geologic subjects (particularly Krakatoa) were shown. The local committee are to be congratulated upon the unusually fine arrangements, with pleasant and convenient accommodations, lunch rooms, and meeting rooms. W. H. Collins, Director of the Geological Survey of Canada, was elected the next President.

Henry S. Washington, who since 1912 has been connected with the Geophysical Laboratory at Washington, D. C., died on January 9.

The recently published 20-volume index (336 pages) of ECONOMIC GEOLOGY for 1905 to 1925, compiled by J. M. Nickles, may be obtained for $3.00 from W. S. Bayley, University of Illinois, Urbana, Ill.

g an ex-
nd Baku
nment.
ureau of
to advise
bility of

vith geo-
Kingston,

Rhodesian
don after

rsaw, on
s in con-
ecretariat

nerica at
from the
lent gen-
rly note-
-Bighorn
re heard.
ociety of
President
ew of the
plex sub-
speeches
cts (par-
be con-
sant and
W. H.
ected the

with the
9.

COLOGY for
om W. S.